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AIDS TO NAVIGATION PRINCIPAL FINDINGS REPORT:

THE EFFECT OF ONE--ETC(U)

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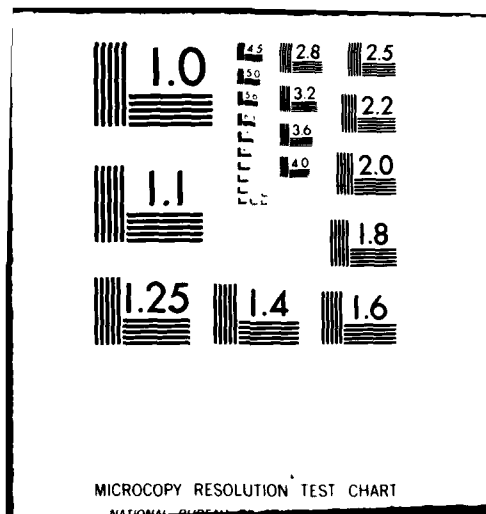
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AIDS TO NAVIGATION PRINCIPAL FINDINGS REPORT:  
THE EFFECT OF ONE-SIDE CHANNEL MARKINGS AND  
RELATED CONDITIONS ON PILOTING PERFORMANCE

Eclectech Associates  
North Stonington Professional Center  
North Stonington, Connecticut 06359



December 1981

Interim Report

Prepared for

U.S. Department of Transportation  
United States Coast Guard  
Office of Research and Development  
Washington, D.C. 20593

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16. Abstract  The experiment described here is one of a series done for the U.S. Coast Guard to quantify the relationship between variables related to aids to navigation and piloting performance in narrow channels and, potentially, safety in such channels. This is one of several experiments restricted to visual piloting, and further to buoys only. It was performed on a simulator built for the U.S. Coast Guard at Eclectech Associates in North Stonington, Connecticut. The variable conditions evaluated were: (1) straight channel markings (buoy configurations were: gated, on one-side inside relative to the turn, on one-side outside relative to the turn, and staggered); (2) turnmarkings (two-buoy and three-buoy turns); (3) buoy height above the water (10-foot and 17-foot buoys); (4) spacing (buoys spaced at 5/8 nm and 1-1/4 nm); and (5) visibility (at 3/4 nm and 1-1/2 nm). The constant conditions were a 500-foot wide channel with a 35-degree noncutoff turn run during the day with wind and current varying over the scenario. The ship was a 30,000 dwt tanker with the bridge 75 feet from the center of gravity, and pilots were instructed to keep transit at 6 knots. The findings of the experiment are presented as the means and standard deviations of crosstrack position of transits under each condition. These are interpreted in terms of their implications for the design of channel markings.			
17. Key Words aids to navigation, piloting, buoy configuration, restricted waterways, channel width, bridge simulation, straight channel marking, turnmarking, controllability, channel boundaries		18. Distribution Statement  Document is available to the public through the National Technical Information Service, Springfield, VA 22161	
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We also wish to thank Captain K. Warner, President of Northeast Marine Pilots Association for his association's continuing cooperation and participation in our simulator research project. Special recognition is due to those pilots who served as subjects during the simulation experiments.



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## PREFACE

The experiment described here is a component of the United States Coast Guard's Performance of Aids to Navigation (AN) Systems project. The project is designed to collect data necessary for guidelines for the design of AN systems. The project includes a survey of U.S. ports to summarize existing conditions, a survey of relevant variables to be considered, a major simulator experiment in visual piloting done at the Maritime Administration's Computer Aided Operations Research Facility (CAORF) in New York, four visual piloting (SRAN) and three radio aids piloting experiments performed on a simulator developed for the project at Eclectech Associates, Inc. in North Stonington, Connecticut. The project also includes an at-sea data collection to validate the USCG/EA simulator and experimental results. The final report will include overall findings for the development of aids to navigation design guidelines.

The experiment described here is the third of four visual piloting experiments performed on the USCG/EA simulator. Visual aids in this experiment were limited to buoys. This experiment evaluates the effect of varying visibility, buoy spacing, buoy size, and buoy configuration on piloting performance. The following is a summary of conclusions supported by the experiment.

- Good piloting performance is dependent on high buoy densities that mark both sides of a channel. Given an equal number of buoys to mark a channel, long-spaced gated buoys is the superior configuration compared to staggered buoys or buoys marking one side of the channel.
- The larger the ambiguity of crosstrack position due to staggered buoys or buoys marking only one side of a channel, the more frequently pilots employ different piloting strategies. These strategies in turn result in more variable and less predictable behavior.
- Buoys immediately following a turn should be located to the outside of the turn. The edges, especially the outside edge, must be marked to provide the pilot information he needs to recover from the turn.
- The three-buoy turn consistently results in satisfactory turn performance regardless of straight channel marking. It provides enough information to complete the turn without relying on whatever straight channel configuration follows. In recovering from the turn, however, performance with one- and two-buoy turns is dependent on the straight channel marking of the new leg.
- When an equal density of buoys mark a channel, gated buoys are better than those marking only one side of a channel under good visibility and staggered buoys are better than those marking one side of a channel when visibility is poor.
- As long as a buoy can be seen, size has no effect on piloting performance.

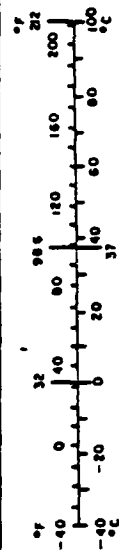
## METRIC CONVERSION FACTORS

### Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
<b>LENGTH</b>				
inches	inches	1	centimeters	cm
feet	feet	30	centimeters	cm
yards	yards	0.9	meters	m
miles	miles	1.6	kilometers	km
<b>AREA</b>				
square inches	square inches	6.5	square centimeters	cm <sup>2</sup>
square feet	square feet	0.09	square meters	m <sup>2</sup>
square yards	square yards	0.8	square meters	m <sup>2</sup>
square miles	square miles	2.6	square kilometers	km <sup>2</sup>
acres	acres	0.4	hectares	ha
<b>MASS (weight)</b>				
ounces	ounces	28	grams	g
pounds	pounds	0.45	kilograms	kg
short tons	short tons	0.9	tonnes	t
(2000 lb)				
<b>VOLUME</b>				
teaspoons	teaspoons	5	milliliters	ml
tablespoons	tablespoons	15	milliliters	ml
fluid ounces	fluid ounces	30	milliliters	ml
cups	cups	0.24	liters	l
pints	pints	0.47	liters	l
quarts	quarts	0.95	liters	l
gallons	gallons	3.8	liters	l
cubic feet	cubic feet	0.03	cubic meters	m <sup>3</sup>
cubic yards	cubic yards	0.76	cubic meters	m <sup>3</sup>
<b>TEMPERATURE (temp)</b>				
Fahrenheit temperature	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

### Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	LENGTH	To Find	Symbol
mm	millimeters	0.04	inches	in	
cm	centimeters	0.4	inches	in	
m	meters	2.3	feet	ft	
m	meters	1.1	yards	yd	
km	kilometers	0.6	miles	mi	
cm <sup>2</sup>	square centimeters	0.16	square inches	inches	
m <sup>2</sup>	square meters	1.2	square yards	yards	
km <sup>2</sup>	square kilometers	0.4	square miles	miles	
ha	hectares (10,000 m <sup>2</sup> )	2.5	acres	acres	
MASS (weight)					
g	grams	0.035	ounces	ounces	oz
kg	kilograms	2.2	pounds	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	short tons	
VOLUME					
ml	milliliters	0.03	fluid ounces	fluid ounces	fl. oz.
l	liters	2.1	pints	pints	pt.
l	liters	1.06	quarts	quarts	qt.
l	liters	0.26	gallons	gallons	gal.
m <sup>3</sup>	cubic meters	35	cubic feet	cubic feet	ft <sup>3</sup>
m <sup>3</sup>	cubic meters	1.3	cubic yards	cubic yards	yd <sup>3</sup>
TEMPERATURE (exact)					
°C	Celsius	9/5 (then add 32)	Fahrenheit temperature	Fahrenheit temperature	°F



## EXECUTIVE SUMMARY

### INTRODUCTION

This simulation experiment is one of a series performed for the United States Coast Guard to quantify the relationship between variables related to aids to navigation and piloting performance in narrow channels. The purpose of this experiment is to evaluate the effect of visibility, buoy spacing, and buoy configuration on piloting performance. The conditions held constant in the experiment were:

- A 500-foot wide channel with a 35-degree noncutoff turn.
- A gusting wind averaging 30 knots throughout the run.
- A 1.5 knot current which decreases to 3/4 knots after the turn and to slack at the end of the run.
- A daylight scene.
- A 30,000 dwt tanker traveling at 6 knots.

The variable conditions in the experiment were:

- Straight channel marking. Buoys only on one side of the channel on the inside relative to the turn, buoys only on one side of the channel on the outside relative to the turn, and a staggered buoy configuration with buoys on both sides of the channel.
- Turnmarking. Two and three buoy turns.
- Buoy size. 10-foot and 17-foot buoys.
- Spacing. Buoys spaced 5/8 nm and at 1-1/4 nm apart.
- Visibility. At 3/4 nm and 1-1/2 nm visual average.

### SUMMARY OF FINDINGS

#### Straight Channel Markings and Buoy Spacing

Piloting performance was compared for the straight channel buoy configurations described above. It was determined that the number of buoys marking a channel was not as important to the pilotage as the manner in which the buoys were arranged. Results of the experiment show gated buoys spaced 1-1/4 nm apart were the superior straight channel marking. These resulted in certainty of ship position, uniformity of piloting strategy, and highly predictable ship tracks. Previous experiments under this program show a reduction of spacing between gates to 5/8 nm (i.e., increasing the number of buoys) did not alone improve performance. Pilots need to see only one gated buoy configuration at a time to maintain a centerline track. Buoy configurations marking only one side of a channel produced a wide dispersion of tracks. This

dispersion represented pilot uncertainty of ship position and subsequently promoted a variety of piloting strategies. These different piloting strategies coupled with position uncertainty made pilot performance inconsistent when buoys were only on one side of the channel. Reducing spacing between buoys on one side by increasing their number did not improve pilot performance. Only when pilots used staggered buoys on both sides of the channel was their performance affected by buoy spacing. Decreasing the number of staggered buoys worsened performance, while increasing the number of staggered buoys improved performance. The following general conclusions are supported:

Good piloting performance is dependent on high buoy densities that mark both sides of a channel. Careful buoy placement is important because buoys control the piloting strategies selected by the pilot and consequently they control tracks. While the pilots never hit a buoy in this simulation, their ships have transitted outside the channel boundaries due to inadequate buoy marking.

The larger the ambiguity of crosstrack position due to staggered buoys or buoys marking only one side of a channel, the more frequently pilots employ different piloting strategies. These different strategies, in turn result in more variable and less predictable behavior.

Given an equal number of buoys to mark a channel, long-spaced gated buoys is the superior configuration; then short spaced staggered buoys, long spaced staggered buoys, and finally buoys marking only one side of the channel.

Pilotage performance in the recovery area beyond the turn was most affected by buoy configuration in straight legs. When buoys marked only the left boundaries and inside of the turn, pilots tended to overshoot beyond the bend onto the right bank. However, when buoys marked only the right boundaries and outside of the turn, pilots were able to stay within the channel beyond the bend. This indicates that the pilots were unable to identify precise ship position from the information provided by the buoys. Specifically, the lack of outside channel markings hampered the pilot's ability to judge the right channel boundary. Performance did not improve when spacing was decreased by adding more buoys on one side.

Piloting performance was also best when the downcurrent side of the channel was well marked. With buoys on the outside of the turn, the pilots were able to avoid being set by the current, and they kept inside the channel. The following general conclusions are supported:

Buoys immediately following a turn should be located to the outside of the turn. For a 35-degree turn, the critical region which must be marked is 950 to 5225 feet in both directions from the point of the bend.

The edges (especially the outside edge) must be marked to provide the pilot with information he needs to recover from the turn.

If buoys marking only one side of the channel are to be used, both angle of the turn and current should be considered. The downcurrent buoy, the boundary toward which the current is moving, is the critical area to be marked.

### Turnmarkings

Two-buoy and three-buoy turns were compared to analyze performance differences with different turnmarkings. Both configurations resulted in acceptable performance, and all pilots agreed that either were adequate for this type of turn. Performance differences between the markings were high trackkeeping inconsistency with the three-buoy marking while preparing for the turn, and a mean track closer to the outside boundary with the two-buoy turn. This latter resulted from a tendency to overshoot the turn with only two buoys. The following general conclusion is supported:

The three-buoy turn consistently results in satisfactory turn performance regardless of straight channel marking. It provides enough information to conduct the turn without relying on whatever straight channel configuration follows. In recovering from the turn, however, performance with one- and two-buoy turns is dependent on the straight channel markings of the next leg.

### Visibility

A scenario with buoys only on one side of the channel and a scenario with buoys staggered on both sides of the channel were run under limited visibility conditions. This simulation compared differences in piloting performance as a function of visibility combined with buoy configuration. Results of these simulations were that low visibility tended to alter pilots' behavior, making them somewhat more conservative and less diverse in their strategies. The result was overall more uniformity in ship tracks with the reduced visibility. Pilotage performance was better when using the staggered buoys in 3/4 nm visibility than when using buoys on one side only in improved 1-1/2 nm visibility. The following general conclusion is supported:

Buoys marking one side of a channel never have an advantage over staggered buoys on both sides even in poor visibility. When using an equal number of buoys (one-side, staggered, or gated configuration), gated buoys are better than one-side configurations in good visibility; and staggered buoys are better than one-side in poor visibility.

### Buoy Size

Buoy size did not affect performance within the range that pilots can see the buoys equally. If a larger buoy can be seen earlier than a smaller buoy, then performance may be improved by the larger buoys. The following general conclusion is supported.

As long as a buoy can be seen, size has no effect on piloting performance.

## Section 1

### INTRODUCTION

#### 1.1 AN OVERVIEW OF THE AIDS TO NAVIGATION PROJECT

The United States Coast Guard is responsible for safety in U.S. harbors and channels and, therefore, for the aids to navigation (AN) necessary to ensure that safety. It is in fulfillment of this responsibility that the Coast Guard is sponsoring a simulator-based program of research into the performance of aids to navigation systems. Their interests include visual aids to navigation, radar, and radio aids. The final objectives of the project are the use of experimental data to derive design criteria for the placement of aids to navigation and to specify radio aids to navigation systems for narrow channels with turns. Completed components of the project are available as separate reports. The first of these was an analysis of the variables expected to affect visual piloting.<sup>1</sup> To enhance the applicability of the findings to real-world harbors, major U.S. ports were surveyed from charts, cataloging the conditions that exist.<sup>2</sup> Three experiments on visual piloting with floating aids have been completed. These are the "CAORF,"<sup>3</sup> "Channel Width,"<sup>4</sup> and "Ship Variables"<sup>5</sup> experiments. The planning of the present experiment is referred to here as the

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<sup>1</sup>W.R. Bertsche and R.C. Cook. "Analysis of Visual Navigational Variables and Interactions." U.S. Coast Guard, Washington, D.C., October 1979.

<sup>2</sup>W.R. Bertsche and R.T. Mercer. "Aids to Navigation Configurations and the Physical Characteristics of Waterways in 32 Major U.S. Ports." U.S. Coast Guard, Washington, D.C., October 1979.

<sup>3</sup>M.W. Smith and W.R. Bertsche. "Aids to Navigation Report on the CAORF Experiment. The Performance of Visual Aids to Navigation as Evaluated by Simulation." U.S. Coast Guard, Washington, D.C., August 1980.

<sup>4</sup>M.W. Smith and W.R. Bertsche. "Aids to Navigation Principal Findings Report on the Channel Width Experiment: The Effects of Channel Width and Related Variables on Piloting Performance." U.S. Coast Guard, Washington, D.C., January 1981.

<sup>5</sup>W.R. Bertsche, D.A. Atkins, and M.W. Smith. "Aids to Navigation Principal Findings Report on the Ship Variables Experiment: The Effect of Ship Characteristics and Related Variables on Piloting Performance." U.S. Coast Guard, Washington, D.C., April 1981.

One-Sided Channel Markings Presimulation Report."<sup>6</sup> Several related studies on radio aid piloting are also complete.<sup>7,8,9</sup>

The first simulator experiment on floating aids to navigation was conducted at CAORF, the Maritime Administration's Computer Aided Operations Research Facility in New York. Later ones, including the one to be described here, were conducted at a simulator built for this U.S. Coast Guard project by Eclectech Associates in North Stonington, Connecticut. Both are bridge simulators, which provide the bridge, the ship hydrodynamics, the environmental effects, and the visual scene necessary for this series of experiments. A comparison of the results obtained on the two is discussed in the Channel Width and Ship Variables reports.

The performance of aids to navigation, and of pilots using aids to navigation, is the result of a complex process under the control of many variables. The 15 variables of interest in the project are listed in Table 1. There are more variables than can be included in a single experiment. Instead, a systems approach which evaluates a part of the process at a time is necessary. The subsets of the relevant variables selected for the first visual experiments are indicated in the table. The emphasis in the first experiments was on varying the conditions that control the amount of visual information buoys provided to the pilot. The visual conditions provided were combined with a complex scenario that required performance in both trackkeeping and maneuvering, with and without perturbations. The general finding of the experiments was a relationship between the maneuvering and/or perturbation requirements of the scenario and the reliance on visual information: when maneuvering was difficult, the pilot's performance was more dependent on the buoy configuration.

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<sup>6</sup>M.W. Smith. "Aids to Navigation Presimulation Report: The Effects of One-Sided Channel Marking and Related Conditions on Piloting Performance." U.S. Coast Guard, Washington, D.C., February 1981.

<sup>7</sup>R.B. Cooper and K.L. Marino. "Simulator Evaluation of Electronic Radio Aids to Navigation Displays - The Miniexperiment." U.S. Coast Guard, Washington, D.C., September 1980.

<sup>8</sup>R.B. Cooper, K.L. Marino, and W.R. Bertsche. "Simulation Evaluation of Electronic Radio Aids to Navigation Displays, The RA-1 Experiment." U.S. Coast Guard, Washington, D.C., January 1981.

<sup>9</sup>R.B. Cooper, K.L. Marino, and W.R. Bertsche. "Simulation Evaluation of Electronic Radio Aids to Navigation Displays, The RA-2 Experiment." U.S. Coast Guard, Washington, D.C., April 1981.

TABLE 1. NAVIGATION PROCESS VARIABLES

VARIABLE	EXPERIMENT
Ship	
Perspective view	Ship Variables
Speed	Ship Variables
Maneuverability	Ship Variables
Channel dimensions	
Banks	
Width	Channel Width
Turn angle	CAORF
Turn radius (configuration)	CAORF
Environmental factors	
Current/wind	CAORF, Channel Width, Ship Variables, One Side
Day/night	CAORF
Visibility/detection distance	CAORF, One Side
Traffic ships	CAORF
AN placement	
Spacing	CAORF, Channel Width, Ship Variables, One Side
Straight channel marking	CAORF, Channel Width, Ship Variables, One Side
Flash period	
Turnmarking	CAORF, Ship Variables, One Side

## 1.2 EXPERIMENTAL CONDITIONS FOR THE ONE-SIDE CHANNEL MARKING EXPERIMENT

The purpose of this experiment is to evaluate the effect on piloting performance of varying visibility, buoy spacing, and buoy configuration. The experimental variables were:

- Straight channel marking. Gated, one-side on the inside relative to the turn, one-side on the outside relative to the turn, and staggered buoy configurations.
- Turnmarking. Two-buoy and three-buoy turns.
- Buoy height above water. 10-foot and 17-foot.
- Spacing. Buoys spaced at 5/8 nm and 1-1/4 nm.
- Visibility. At 3/4 nm and 1-1/2 nm.

The experimental conditions and comparisons are shown by Table 2 and outlined by Table 3. The scenarios are diagrammed in Appendix A. The hypotheses associated with the selection of these variables were as follows:

TABLE 2. EXPERIMENTAL CONDITIONS

Scenario	Straight Channel Marking	Visibility	Spacing (nm)	Turnmarking	Buoy Height Above Water (feet)	
FAM	gated	1-1/2	5/8	three	10	
1	gated	1-1/2	1-1/4	three	10	
2	inside	1-1/2	1-1/4	three	10	
4	inside	1-1/2	5/8	three	10	7x17
5	outside	1-1/2	5/8	three	10	
6	gated	1-1/2	1-1/4	two	10	
7	inside	1-1/2	1-1/4	three	17	9x32
8	inside	3/4	5/8	three	10	
9	staggered	3/4	5/8	three	10	

TABLE 3. AVAILABLE COMPARISONS BY SCENARIO NUMBER

VARIABLE	SCENARIOS
EFFECT OF STRAIGHT CHANNEL MARKING WITH EQUAL SPACING Gated versus one-side configuration	1 versus 2
EFFECT OF STRAIGHT CHANNEL MARKING WITH EQUAL DENSITY Gated versus one-side inside configuration	1 versus 4
Gated versus one-side outside configuration	1 versus 5
One-side inside versus one-side outside configuration	4 versus 5
EFFECT OF BUOY SPACING WITH ONE-SIDE CONFIGURATIONS Closed (5/8 nm) versus open (1-1/4 nm) spacing	2 versus 4
EFFECT OF TURNMARKING Two versus three turn buoys	1 versus 6
EFFECT OF LIMITED VISIBILITY 3/4 nm versus 1-1/2 nm visibility	4 versus 8
One-side inside versus staggered configuration	8 versus 9
EFFECT OF BUOY HEIGHT 10-foot versus 17-foot height	2 versus 7

1. Effect of Straight Channel Marking. In the early planning for this project,<sup>10,11</sup> it was hypothesized that the important factor in straight channel marking is the alongtrack distance between aids abeam. If this is true, one-side marking offers obvious savings over gated marking. Comparing scenarios 1 and 2 tests this hypothesis. Scenario 1 is a gated buoy condition and scenario 2 is a one-side buoy condition with buoys on the inside relative to the turn and on the upcurrent side of the channel. The 1-1/4 spacing was selected because two earlier experiments (CAORF<sup>12</sup> and Channel Width<sup>13</sup>) showed this spacing was adequate with gates: 5/8 spacing did not substantially improve performance. It was necessary, however, to modify the original hypothesis on the basis of intervening experiments. Both the CAORF and the Channel Width experiments presented evidence that gated buoy conditions have an advantage over staggered buoys at the same absolute alongtrack distance. It can be inferred from earlier results that gates may also have this advantage over the one-side markings.

2. Effect of Alternative Straight Channel Marking With Equal Density. This comparison reuses scenarios already described to evaluate alternative arrangements of equal density (the number of buoys per unit distance) buoys. Scenario 1 has gated buoys spaced at 1-1/4 nm; scenario 4 has one-side marking spaced at 5/8 nm on the inside of the channel relative to the turn; scenario 5 has one-side marking spaced at 5/8 nm on the outside of the channel relative to the turn.

3. Effect of Buoy Spacing. The experiment includes a variation in spacing for the one-side marking conditions. Scenario 4 is comparable to scenario 2 since it too has one-side marking on the inside relative to the turn, but at a 5/8 rather than 1-1/4 nm spacing. These comparisons quantify the effect of spacing on one-side marking conditions. U.S. ports surveyed<sup>14</sup> in planning for this project found that the mean spacing for one-side marking in channels of width similar to these is 7/8 nm. Therefore, the shorter, 5/8 nm, spacing is more representative of actual conditions than is the longer, 1-1/4 nm, spacing.

4. Effect of Turnmarking. Scenario 1 has three buoys marking the turn and long-spaced gated buoys marking the straight channel. Scenario 6 has the same straight channel marking but only two buoys in the turn. The straight channel marking is the same for both conditions. The CAORF

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<sup>10</sup>W.R. Bertsche and R.C. Cook, op. cit.

<sup>11</sup>W.R. Bertsche and R.T. Mercer, op. cit.

<sup>12</sup>M.W. Smith and W.R. Bertsche, op. cit., August 1980.

<sup>13</sup>M.W. Smith and W.R. Bertsche, op. cit., January 1981.

<sup>14</sup>W.R. Bertsche and R.T. Mercer, op. cit.

and Channel Width experiments<sup>15,16</sup> showed that the marking in scenario 1 is sufficient to support a smooth turn and pullout. An earlier experiment performed at CAORF for a different project<sup>17</sup> showed the two-buoy turn to be inadequate: there was a tendency to wait to pass through the gate before beginning the turn and to go out of the channel beyond as a result. Since the survey of U.S. ports<sup>18</sup> found the two buoys to be the most frequent turnmarking and because many pilots express a preference for it, it is worthwhile to replicate the earlier evaluation.

5. Effect of Visibility. These comparisons assess the impact of reduced visibility on piloting. Scenarios 4 and 8 are identical (one-side inside buoys spaced at 5/8 nm) except that visibility is at 1-1/2 nm for scenario 4 and at 3/4 nm for scenario 8. In 3/4 nm visibility, the pilots could see only one buoy at a time while in 1-1/2 nm visibility the pilots could see two buoys on one side. Scenario 8 is reused to compare it with scenario 9, a staggered version of the one-side buoy scenario. The staggered configuration is compared to the one-side 5/8 spacing configuration because there are the same number of buoys marking the channel. The difference is the buoys are staggered on either side of the channel boundaries instead of located on one side of the channel. The staggered scenario buoys have 1-1/4 nm spacing along one side, but the buoy-to-buoy spacing is at 5/8 nm. This means that under both scenario conditions, the pilots saw a buoy at the same alongtrack position.

6. Effect of Buoy Size. Scenario 7 is simulated with buoys that are 9 by 32 feet with 17 feet above the water. This is the size that has been used in all experiments to date. Scenario 2 is identical except for the height and detail of the buoys. For this experiment, all scenarios other than scenario 7 use this modified buoy. The new buoy is 7 by 17 feet with 10 feet above the water. The buoys are open and have legs to provide more realism. This smaller buoy was the smallest that is likely to be found in a 40-foot deep channel transited by tankers.<sup>19</sup> This comparison evaluates the effect of buoy size effect on performance.

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<sup>15</sup>M.W. Smith and W.R. Bertsche, op. cit., August 1980.

<sup>16</sup>M.W. Smith and W.R. Bertsche, op. cit., January 1981.

<sup>17</sup>D.A. Atkins and W.R. Bertsche. "Restricted Waterways Experiment IIIA Data Analysis and Findings." National Maritime Research Center, October 1978.

<sup>18</sup>W.R. Bertsche and R.T. Mercer, op. cit.

<sup>19</sup>Telephone conversation with USCG Office of Engineering, Ocean Engineering Division, February 1981.

### 1.3 CONDITIONS CONSTANT TO ALL SCENARIOS

The experimental comparisons of interest are made in a context of appropriate constant conditions. The comparisons among the experimental conditions are specific to the constant conditions and might not show the same differences if the constant conditions were changed. Therefore, it is necessary to use the same care in the selection of the constant conditions as in the selection of the experimental conditions. The constant conditions chosen here are similar to those that appeared as constant or varied in previous experiments. This similarity maximizes comparability between experiments. The selected conditions are summarized in Table 4.

1. The Channel Dimensions. The scenario contains two channel segments, 2 and 2-1/2 nm long, connected by a turn. The channel is 500 feet wide and was chosen after the Channel Width experiment<sup>20</sup> demonstrated that this width, rather than the wider width to which it was compared, requires greater understanding of the channel marking. One foot of clearance under the ship was necessary to obtain the planned maneuverability.

2. The Turn Characteristics. The turns in this experiment were 35-degree noncutoff turns because the CAORF experiment<sup>21</sup> showed this turn was the more difficult. Such a turn was chosen to be sufficiently difficult to represent the perturbation of a wide range of turns yet realistic enough to provide a pullout that would not contaminate straight channel performance beyond.

3. Environmental Conditions. The daytime and 1-1/2 nm visibility conditions that successfully revealed differences in aids to navigation conditions in the Channel Width experiment<sup>22</sup> were retained. The current and wind follow patterns similar to that used in the Channel Width and identical to that in the Ship Variables experiment.<sup>23</sup> The wind is following in the first leg and broad on the port quarter after the turn, with some variation in direction. The wind speed is 30 knots with some variation. The current, too, is following in the first leg and broad on the port quarter after the turn. It decreases in velocity from 1-1/4 knots at the beginning of the scenario to 3/4 knots after the turn to zero at the end of the run. The wind and current are shown in Figure 1.

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<sup>20</sup>M.W. Smith and W.R. Bertsche, op. cit., January 1981.

<sup>21</sup>M.W. Smith and W.R. Bertsche, op. cit., August 1980.

<sup>22</sup>M.W. Smith and W.R. Bertsche, op. cit., January 1981.

<sup>23</sup>W.R. Bertsche, D.A. Atkins, and M.W. Smith, op. cit.

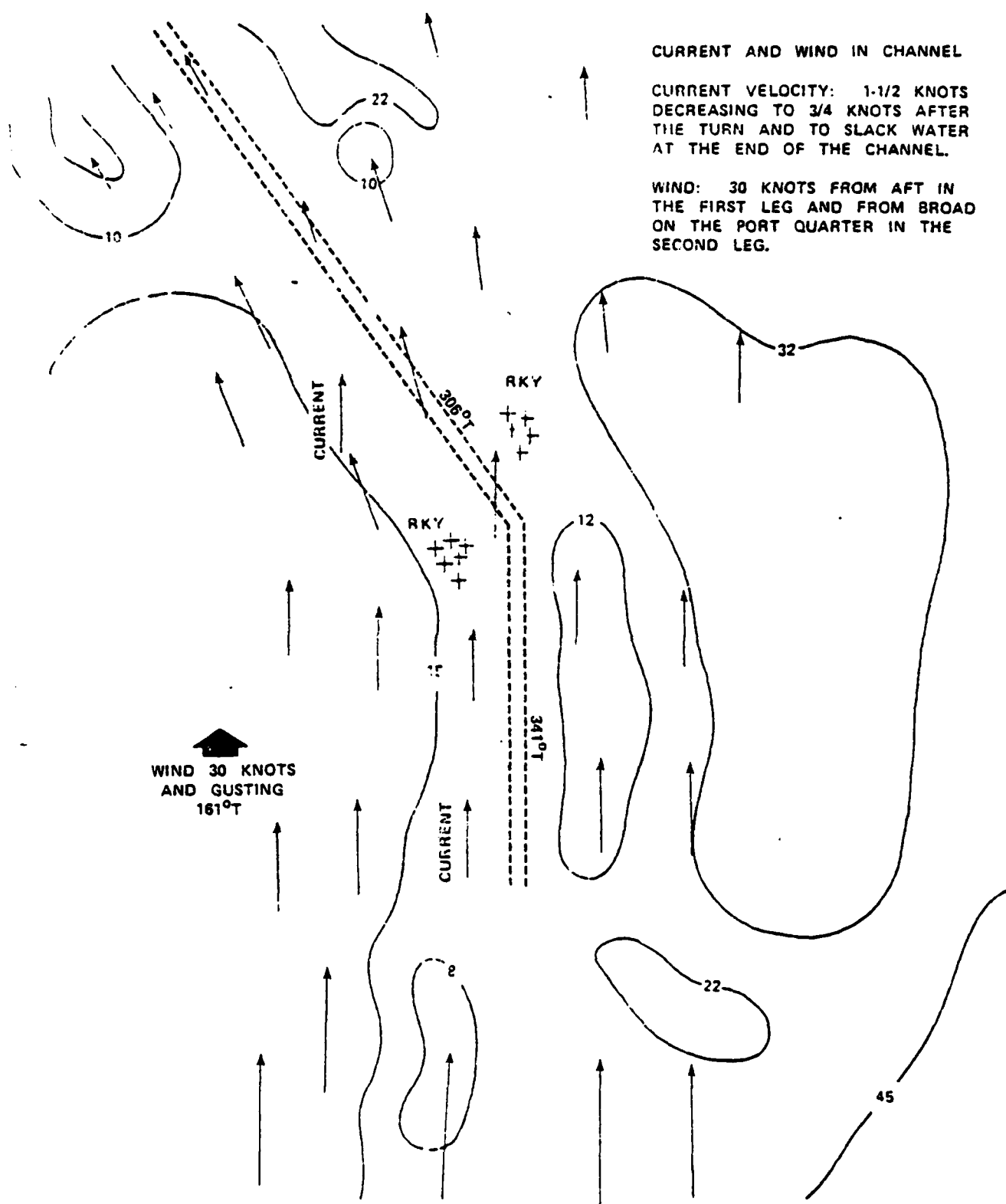


Figure 1. Current and Wind in Channel

TABLE 4. THE CONSTANT CONDITIONS

1. Channel Dimensions:
  - 2, 2-1/2 nm length
  - 500-foot width
  - Shallow depth
2. Turn Characteristics:
  - 35-degree noncutoff turn
3. Environmental Conditions:
  - Daytime
  - Wind and current vary over scenario
4. Bridge Conditions:
  - Helmsman
  - Engine order telegraph
  - Gyrocompass
  - Chart
5. Visual Scene:
  - Ship's bow
  - Sea, sky demarcation at 1-1/2 nm
  - Red, black buoys at 1-1/2 nm
6. Performance Requirements:
  - Move to centerline with following current
  - Align ship to turn
  - Make turn
  - Stabilize ship after turn with decreasing crosscurrent
  - Maintain channel centerline with decreasing crosscurrent

4. The Bridge Conditions. The pilot has available the following:

- A helmsman to receive his orders.
- A gyrocompass.
- An engine order telegraph (with the opportunity occasionally taken to increase his speed in the turn).
- Charts of the channel with the course and buoy locations.
- A diagram of the current conditions.
- No radar. (This is an experiment in visual piloting.)

5. The Visual Scene. A sample visual scene used during the scenario is illustrated in Figure 2. Because bow image did not make a difference in Leg 2, performance in the Ship Variables Experiment and because the One-side Marking experiment is using very little of Leg 1, the realism and detail of the bow image was improved to please the pilots. The 30,000 dwt tanker has a 45-foot height of eye. The eye point was located 75 feet forward of the ship's center of gravity. The daytime

detection range is represented by a gray sea and blue sky. Two sizes of buoys were modelled. The 10-foot "open" buoy had a cylindrical base which supports struts and a radar reflector. The 17-foot "solid" buoy had a cylindrical base and a cylindrical solid superstructure. Images on the bridge wings block out the buoys just before they pass abeam.

6. The Performance Requirements. The piloting tasks the pilot is instructed to perform are illustrated in Figure 3. The ship was initialized 1.3 nm below the turn and 100 feet to the right of the centerline. At that point there was a following current which decreased from 1.5 knots and a following wind of 30 knots and gusting. The pilot was instructed to take the ship to the designated trackline. He could leave that trackline when ready to negotiate the turn by his own strategy. He was asked to return to the designated track in the next leg as soon as possible. As he entered the new leg, the wind and current were broad on his port quarter. Given the current velocity of  $3/4$  knots and his speed through the water of  $6-1/2$  knots, he needed a drift angle of 3 degrees to maintain the course of the channel. As he attempted to return to the designated trackline, the current velocity, and the necessary drift angle decreased, reaching zero at the end of the scenario. The wind remained the same in direction and average intensity throughout the run. The instructions to the pilot and the postsimulation questionnaire appear as Appendix B. The wind and current effects are described more specifically in Appendix C.

#### 1.4 DATA COLLECTION AND ANALYSIS

##### 1.4.1 Data Collection

A variety of performance measures were collected for use in evaluating the scenario conditions. These include:

1. The ship's crosstrack position as a function of alongtrack position. (The graph of this relationship is referred to as a track plot.) A variety of related dependent variables are also recorded. When the ship crosses the data lines diagrammed in Figure 4 or when the pilot makes the responses described below, the computer records the following measures:

- Time of event.
- Ship's center of gravity position.
- Ship's bridge position.
- Ship's velocity relative to the ground.
- Ship's true heading.
- Rate of turn.
- Rudder angle.
- Course made good.
- RPM of propeller.

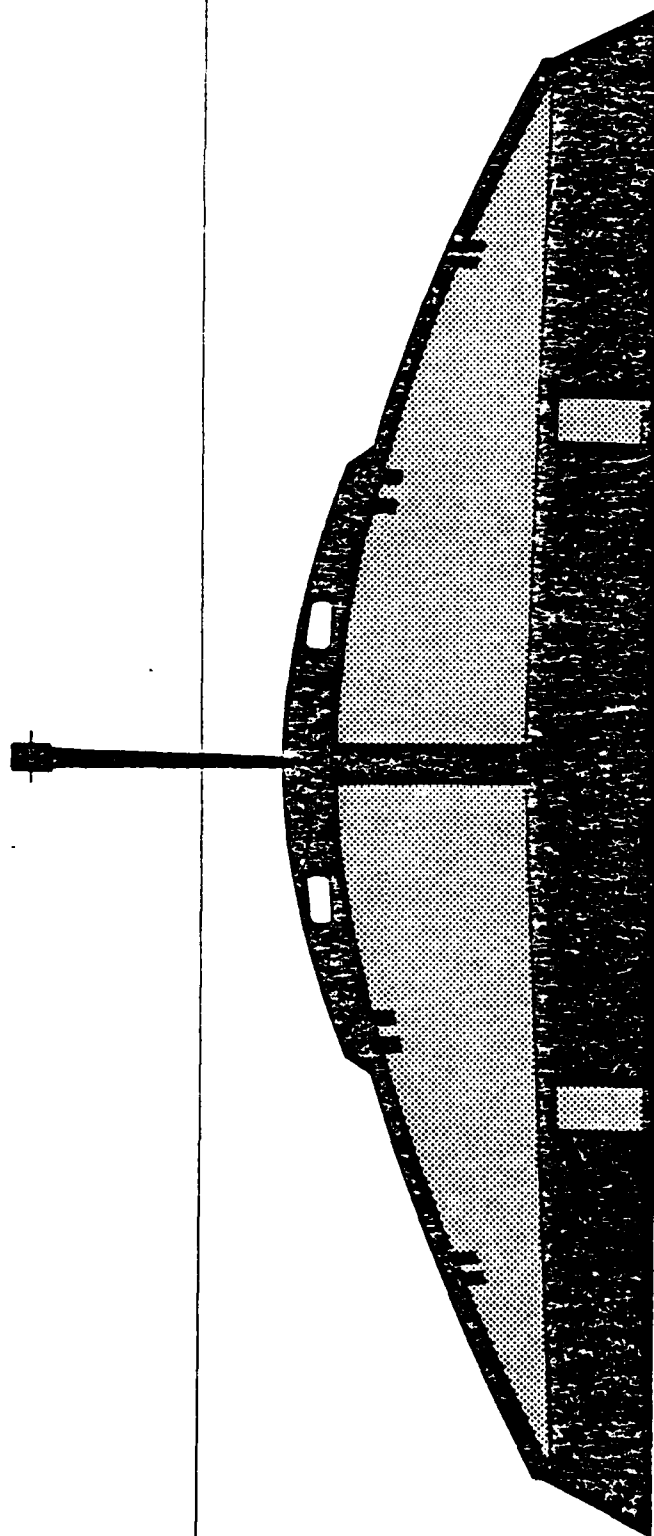


Figure 2. The Visual Scene

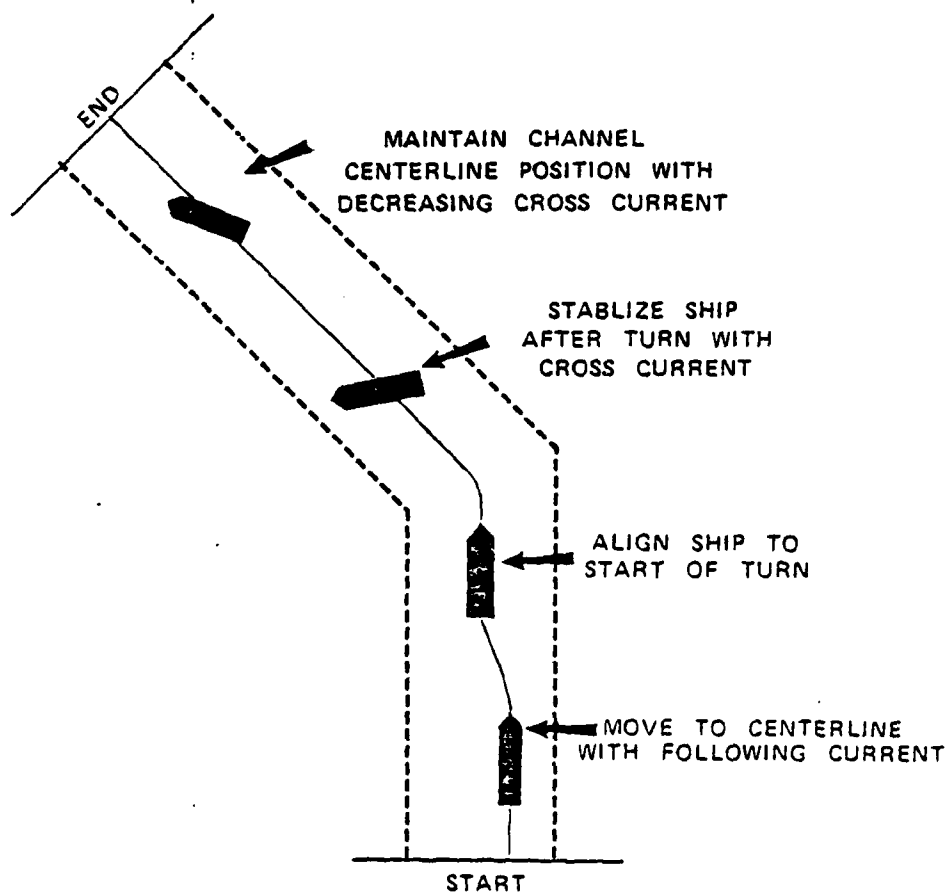


Figure 3. Performance Requirements

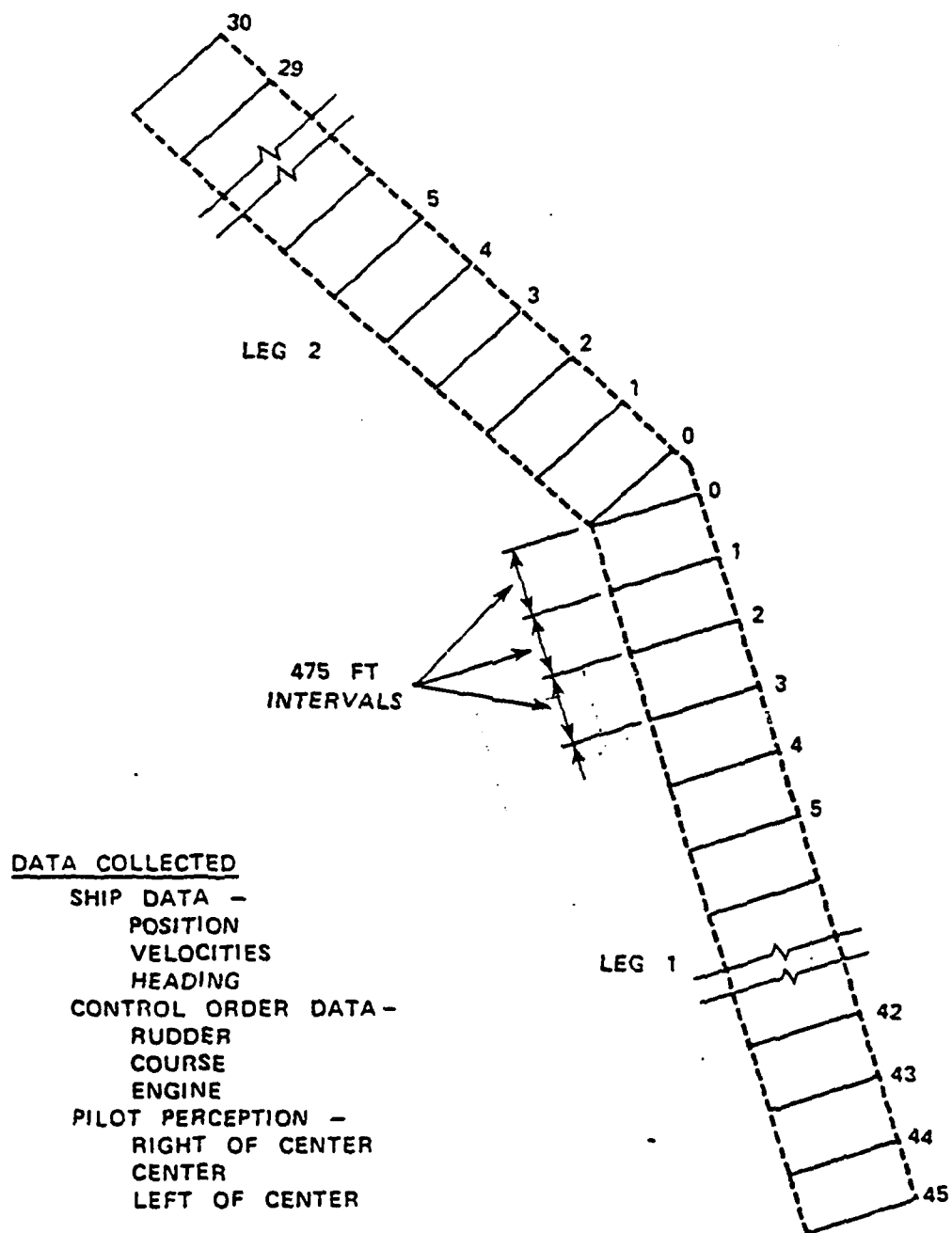


Figure 4. Data Collection Lines

2. The subject's course, rudder, and engine orders are recorded with alongtrack position and a variety of other dependent measures.

3. A postsimulation questionnaire allows the subject to comment subjectively on the conditions of each scenario and his strategies. This questionnaire appeared in the presimulation report cited earlier and formed the basis for the preliminary observations.<sup>24</sup>

#### 1.4.2 Descriptive Analysis of the Data

The principal descriptive analysis is a compilation of data on the position of the ship's center of gravity. The basic measure of the ship's crosstrack position is treated as illustrated in Figure 5. The mean and standard deviation are calculated at each data line for the set of conditions to be described. The first set of axes shows the means; the second, the standard deviation. On the last axes is a "combined plot" which shows the band formed by the mean and two standard deviations to either side of it against the boundaries of the channel. The band encloses 95 percent of expected transits under the experimental conditions sampled. The placement (mean) and width (standard deviation) of this band within the boundaries of the channel are together a quantitative description of the set of transits under these conditions, and, therefore, of the performance of the buoy arrangements.

The trackkeeping portions of the scenario are the easiest to interpret. It is assumed that, because of instructions, the pilots are attempting to keep the ship on the designated track. The distance of the mean off the centerline and the spread measured by the standard deviations are indications of the performance of the buoy arrangement for the conditions sampled. Therefore, the best buoy arrangement is one that puts the mean of the distribution on the centerline and minimizes the standard deviation. Performance in the maneuvering portions is more difficult to interpret. The distribution of crosstrack portions contains the variations in pilots' strategies as well as the performance of the buoys in guiding them in those strategies. An adequate buoy arrangement should keep the combined plot well inside the channel.

There is an assumption in this discussion that the precision in piloting performance afforded by buoy arrangement is related to the safety of that channel: a safely marked channel is one that results in a distribution of transits that is well within the channel boundaries for both trackkeeping and maneuvering. It should be reemphasized that these measures are derived from an experiment and not a real-world situation. They are measures of performance under the experimental conditions (the experimental design and the simulation) used. For application to real-world channels, they must be considered relative

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<sup>24</sup>Eclectech Associates. "Preliminary Observations of the One-Sided Channel Marking Experiment." April 1981.

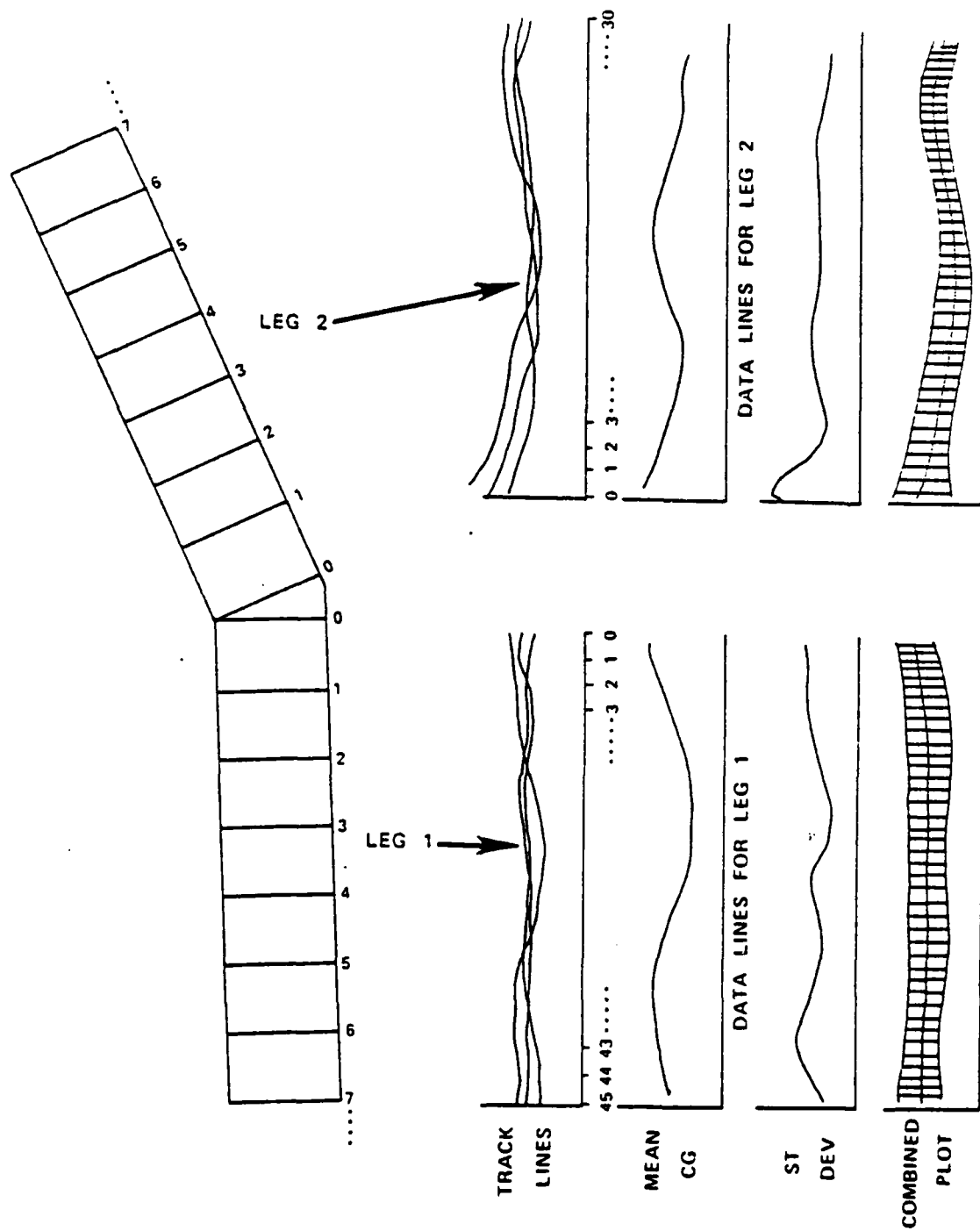


Figure 5. Descriptive Analysis of Ship's Center of Gravity

measures of the performance of buoy arrangements of channel conditions. The interpretation of these performance measures as probability of grounding, for example, would be incorrect pending validation of such interpretation in the real world.

#### 1.4.3 The Inferential Tests

The experiment cannot be analyzed with any single inferential procedure for the following reasons.

1. Each comparison is logically a separate experiment.
2. To adequately describe the data (the crosstrack position of the ship's center of gravity) requires both the mean and the standard deviation (or variance), and these must be calculated at each data line over the scenario.

Instead, for each separate comparison the mean and standard deviations for each component scenario will be selected at critical data lines and tested for the significance of their differences by the following procedures which are described in McNemar.<sup>25</sup> When means from two conditions are to be compared, a t-test will be used. The standard deviations of the conditions will be compared in pairs dictated by the logic of the comparisons. They will be compared as variances, using variance ratios, or an F-test.

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<sup>25</sup>Quinn McNemar. Psychological Statistics, Fourth Edition. John Wiley and Sons, Inc., New York, 1969.

## Section 2

### PERFORMANCE AS A FUNCTION OF STRAIGHT CHANNEL MARKING AND BUOY SPACING

#### 2.1 OVERVIEW

Various straight channel buoy configurations were compared to evaluate their effect on piloting performance to determine the most optimal arrangement. The configurations available were:

- Gated spaced 1-1/4 nm apart (scenario 1)
- One-side inside relative to the turn spaced 1-1/4 nm apart (scenario 2)
- One-side inside relative to the turn spaced 5/8 nm apart (scenario 4)
- One-side outside relative to the turn spaced 5/8 nm apart (scenario 5)

All scenarios appearing in this section were run in 1-1/2 nm visibility with 10-foot high buoys and a three-buoy turnmarking.

Results of the experiment show gated long-spaced buoys to be the superior straight channel marking when compared to one-side configurations. Shortened spacing for one-side buoy configurations did not significantly improve performance.

Performance with one-side buoys did not conform with hypotheses. Mean tracks were expected to favor the buoy side, but this did not occur. Piloting performance was unsatisfactory with inside buoys since in leg 2 some of the combined track plot fell outside of the channel. This occurred because the lack of outside channel markings hampered the pilot's ability to judge the right channel boundary. The outside buoy condition resulted in adequate performance. This, however, seems to have resulted more from the given wind and current rather than pilot performance. As wind and current decreased toward the end of leg 2 performance with outside buoys worsened by a widening dispersion of tracks. Therefore, both inside and outside one-side configurations resulted in inferior piloting performance.

In summary, given an equal density of buoys, long-spaced gated buoys are the superior buoy configuration when piloting in 1-1/2 nm visibility. If one-side buoys are ever to be used, environmental factors must be carefully evaluated to ensure safety.

#### 2.2 EFFECT OF STRAIGHT CHANNEL MARKING WITH EQUAL BUOY SPACING

Scenario 2 is a one-side version of gated scenario 1. The buoys mark the inside of the channel relative to the turn and are on the upcurrent side. In both scenarios the buoys are spaced at 1-1/4 nm apart except

at the turn which is marked by three buoys. Visibility in both scenarios is at 1-1/2 nm. The scenarios are shown in Figure 6.

The comparison of these scenarios shows that performance with buoys on one side of the channel cannot compare to performance with gated buoys with all other factors held constant. Piloting performance differences between the two scenarios is shown in the combined track plots in Figure 7. These plots are shown as a continuous linear plot with the turn having occurred at data line 0. The data depicts the mean track  $\pm 2$  standard deviations in the crosstrack direction. This envelope encloses 95 percent of the expected transits under the experimental conditions sampled. Data are plotted for every data line where data lines are 475 feet apart.

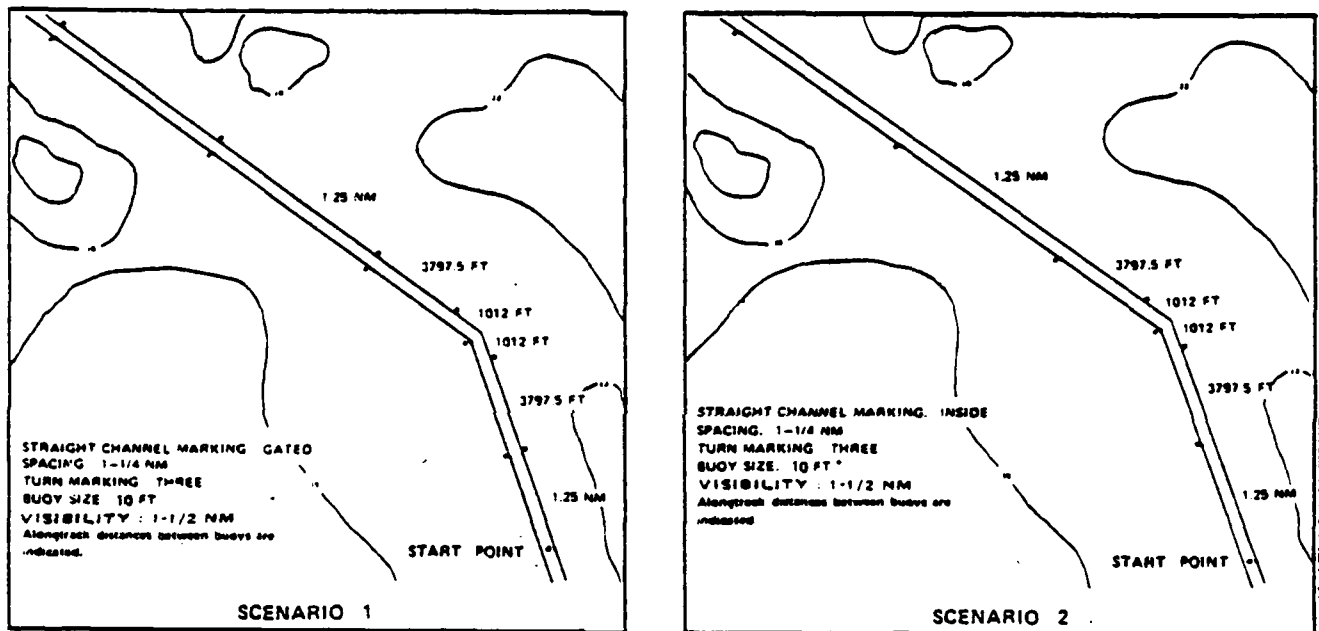


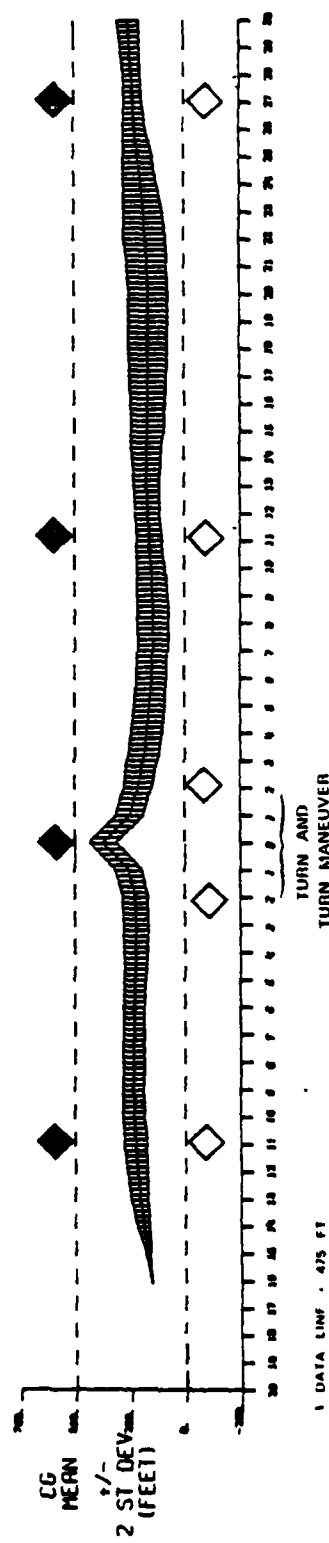
Figure 6. Scenarios 1 and 2

Figure 7 indicates that gates are the superior aid to navigation because pilots can judge the ship position with certainty. As hypothesized in the one-side presimulation report,<sup>26</sup> the gated condition shows the mean closest to the centerline with the smallest standard deviation. This is due to the pilots' dominant strategy of passing equidistantly between the buoys and the pilots' certainty in judging the ship's position and the ship's movement.

Performance with the one-side buoys resulted in a poorer mean track and a wide dispersion (standard deviation) of tracks. This was also as

<sup>26</sup>M.W. Smith, op. cit.

# SCENARIO 1: GATED CHANNEL MARKINGS AT 1 1/4 NM APART



# SCENARIO 2: INSIDE CHANNEL MARKINGS AT 1 1/4 NM APART

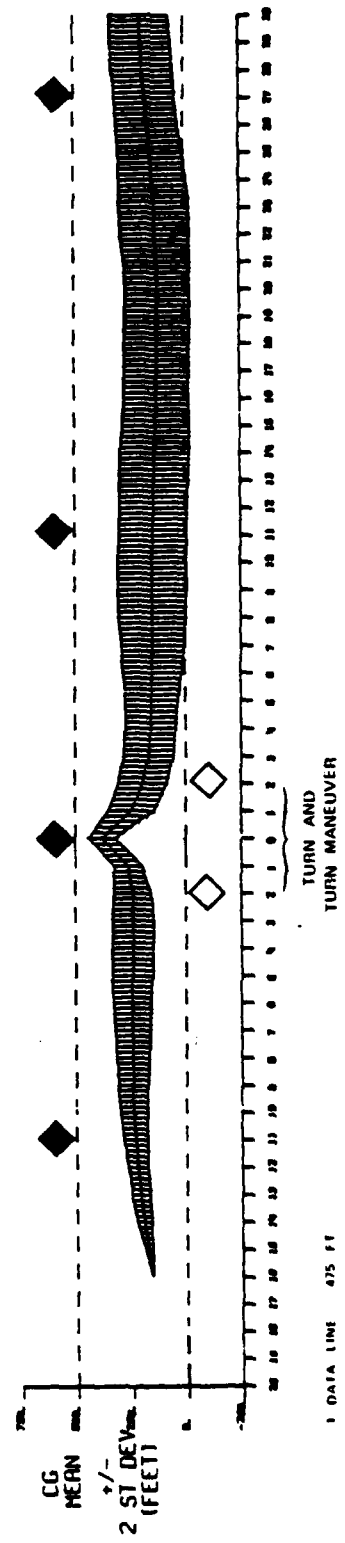


Figure 7. Combined Plots of Piloting Performance: Gated 1 1/4 nm Spaced Buoys Versus One Side 1 1/4 nm Spaced Buoys in 1 1/2 nm Visibility

expected. However, the original hypothesis was that the mean track for the one-side scenario would favor the side the buoys were on and this did not occur. In most of leg 2, the combined plot exceeded the channel boundary showing that some pilots had difficulty judging the ship's position and steering to compensate for the wind and current effects. The one-side buoy system resulted in uncertainty of ship position because there was no line of buoys to use as a reference (closer one-side spacing) and only one reference buoy instead of two (gates). The mean track for this scenario does not represent a dominant strategy but rather it represents a nondescript combination of many strategies. The strategies (from the preliminary observations<sup>27</sup>) were: (1) counter the natural tendency to run close to the buoys by intentionally steering away from the buoys resulting in an overcompensation (out of channel); (2) combine zigzagging and hugging, that is to crowd into the buoys then haul off; (3) compare the distance off the buoy to the bow width to try to judge the center of the channel; and (4) steer the course of the channel periodically to use the ship as a measurement instrument. The use of many different strategies and the pilots' uncertainty of ship position is reflected in the wide standard deviation.

A statistical comparison of the two conditions in both mean crosstrack location and standard deviation is shown in Figure 8. These data indicate that there is a significant increase in the standard deviation at the 0.10 level of significance for the one-side straight channel buoy marking which occurs along most of the channel length. Additionally, the mean crosstrack location appears to be significantly different in the last segment of leg 2. These differences are discussed by regions associated with the different maneuvering problems.

Behavior differences in leg 1 are confined to region 1 from data lines 7 through 4 as indicated in Figure 8. This is the area where the pilot is returning to and steady up on the centerline from a 100-foot displacement to the right of the centerline. The pilots were instructed to return to the channel centerline and transit down the center of the channel throughout the run except to maneuver in the turn. In region 1, the means for both conditions are very close to the centerlines but the standard deviation for the one-side scenario is significantly larger than the gated scenario. Table 5 shows the mean and standard deviation for this region.

The distance required to return to the centerline and steady up in leg 1 is almost identical under both conditions. The mean overshoot following the return is very small for the gated condition and nonexistent for the one-side condition. Figure 8 shows the region 1 mean as being very close to the centerline. At data line 11, the point at which the ship reaches the centerline, the standard deviation for the one-side condition increases and pulls away from the gated condition. This is because the pilots had difficulty identifying the center of the channel with one-side buoys so tracks are dispersed. Although the mean overshoot for one-side buoys is only 1 foot to the right of the

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<sup>27</sup> Eclectech Associates, op. cit.

STRAIGHT CHANNEL BUOY MARKING WITH EQUAL SPACING

— GATED (SCEN 1)  
 --- INSIDE (SCEN 2)

10.0 - AREAS WHERE THE PROBABILITY OF DIFFERENCE  
 OCCURRING BY CHANCE IS LESS THAN 10%

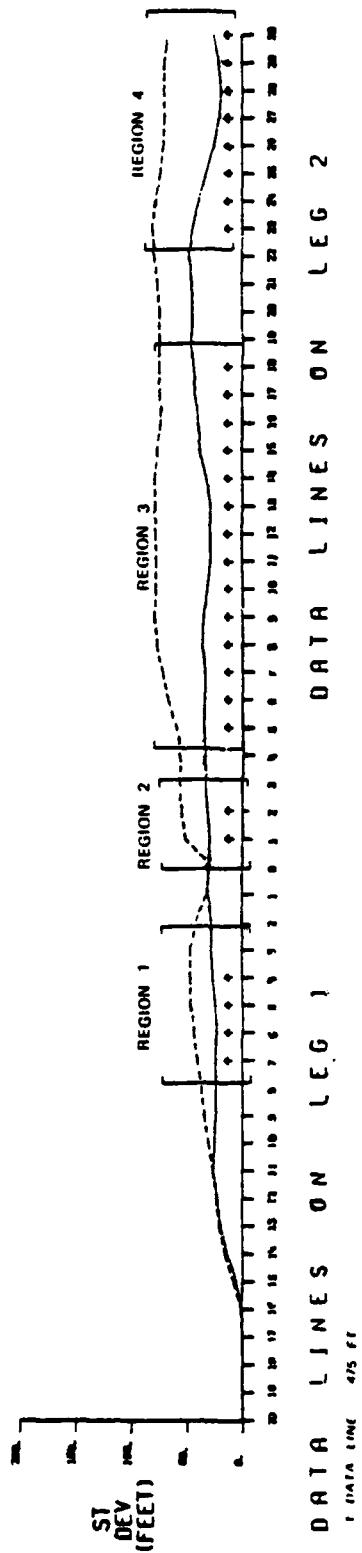
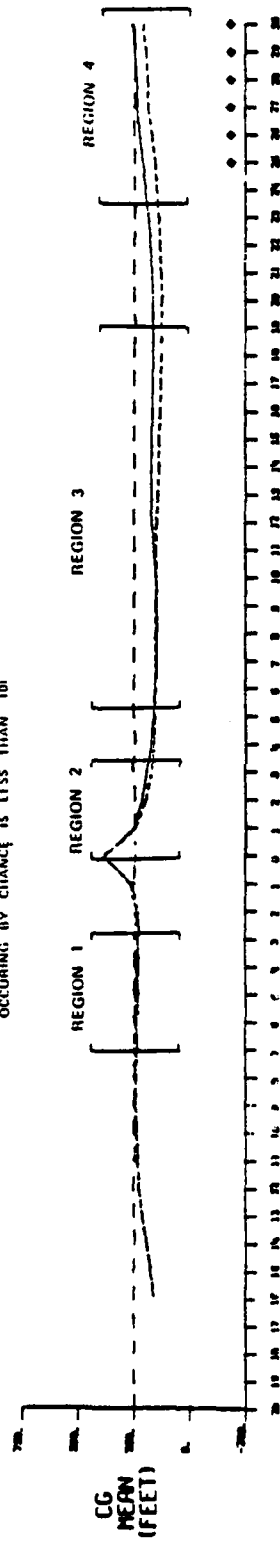


Figure 8. Crosstrack Mean and Standard Deviation of Piloting Performance:  
 Gated 1 1/4 nm Spaced Buoys Versus One Side 1 1/4 nm Spaced Buoys in 1 1/2 nm Visibility

TABLE 5. MANEUVERING ANALYSIS - RETURN TO  
AND STEADY UP ON CENTERLINE FOR REGION 1

GROUP MEAN		
Performance Measure	Gated (Scenario 1)	Inside (Scenario 2)
Distance to return to centerline (feet before turn)	5043	5590
Overshoot following return to center- line (feet away from centerline)	21.7R	6.5R
Distance to steady up in Leg 1 (feet before turn)	4739	4739
STANDARD DEVIATION		
Performance Measure	Gated (Scenario 1)	Inside (Scenario 2)
Distance to return to centerline (feet before turn)	972	547
Overshoot following return to center- line (feet away from centerline)	24.8	46.8*
Distance to steady up in Leg 1 (feet before turn)	972	972
*Probability less than .10 of occurring by chance R = Right of Centerline		

centerline, the standard deviation is 44 feet. This reflects the wide dispersion in ship position (from 84 feet to the right for one subject to 79 feet to the left for a second subject). The standard deviation decreases as the pilots prepared for the turn.

Figure 9 shows the position of ownship through the turn. The turn initiation for both conditions are similar but the one-side condition has a higher standard deviation. The first turn buoy is positioned at data line 2 (950 feet before the turn). From this point to the black turn buoy positioned at data line 0, the standard deviation for the one-side condition decreases while the standard deviation for the gated condition remains approximately constant. In the vertex of the turn both tracks are similar with the ship positioned to the left to hug the buoy. The standard deviation, however, increases at a greater rate for the one-side condition in recovering from the turn (shown by region 2 of Figure 8). This is due to the relative uncertainty as to the location of the centerline and the channel boundaries of the new leg. This may

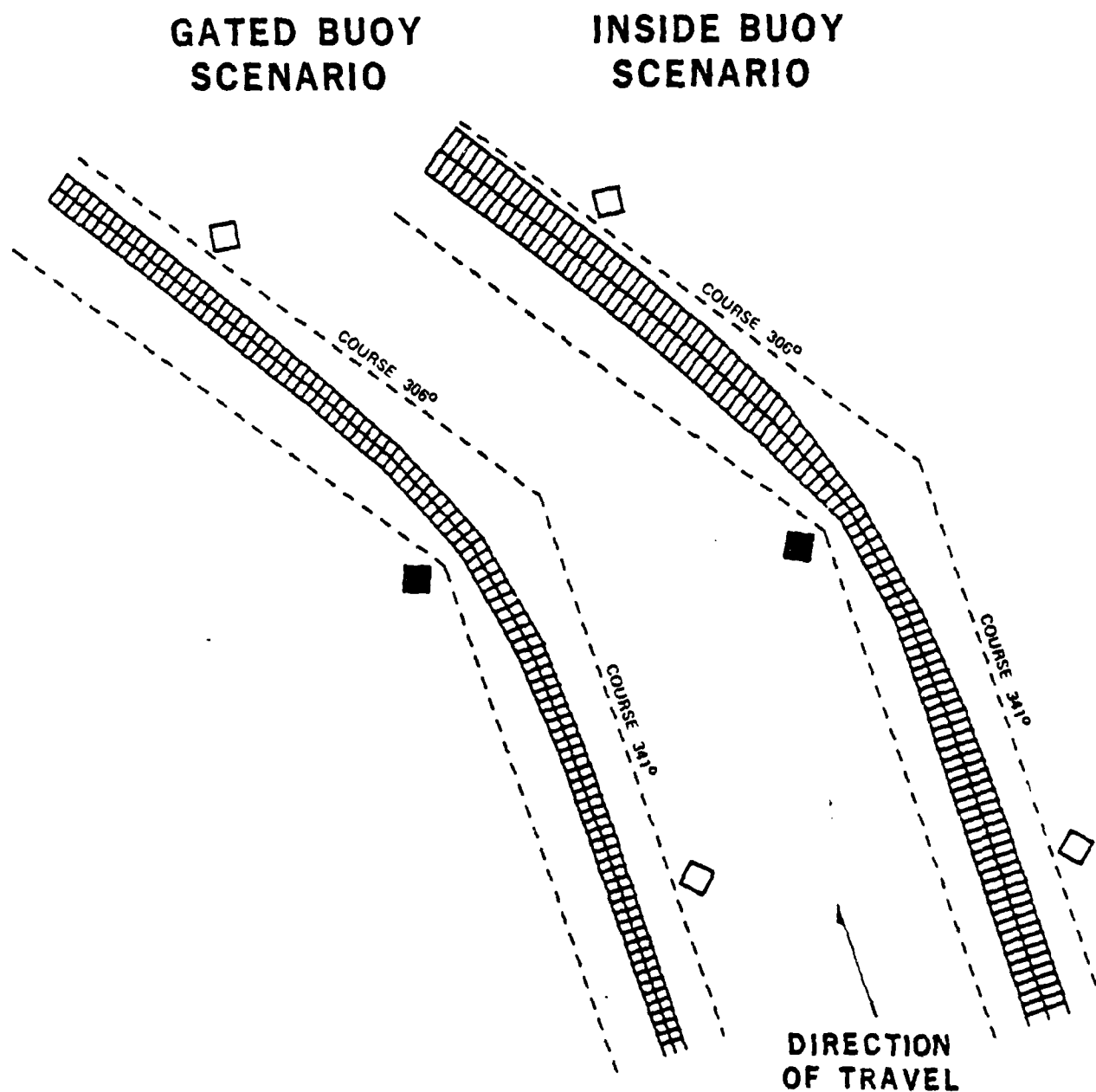


Figure 9. Turns for Gated Versus One Side Straight Channel Markings

have contributed to a tendency for pilots to apply the check rudder earlier for the one-side condition than the gated condition. (The mean check rudder was applied at data line 0 for the one-side condition and data line 1 for gated for a 475-foot alongtrack difference in mean check rudder application). Throughout leg 2 of the one-side scenario, the ship is swept downcurrent and never returns to the centerline.

Region 3 shows a high crosstrack standard deviation in the area of leg 2 immediately following the turn. The maximum dispersion of tracks occurs for scenario 1 at data line 18 with a standard deviation of 44 feet and for scenario 2 at data line 13 with a standard deviation of 79 feet. The large standard deviation that occurs in leg 2 with the one-side condition results largely from uncertainty of ownship position and the crabbing and weathervaning caused by the wind and current. This coupled with poor information available to the pilots caused the unsatisfactory performance in leg 2.

Region 4 is the last segment of leg 2 which shows not only a significant difference in standard deviations but also a significant difference between the means. The improvement in the gated condition mean results from the decreasing velocity of the current. It reaches 0 knots near the end of the scenario so the pilot needs only to steer the appropriate course without having to compensate for environmental factors. The one-side tracks do not correspondingly improve with the improved environment because the pilots were unable to judge channel boundaries.

In discussing one-side performance, it should be pointed out that before using one-sided buoys, the pilots had run through three gated scenarios; a familiarization run, and two gated runs. This was because the gated scenarios have different turnmarkings which are being compared (see section 4). Analysis of the Ship Variables experiment<sup>28</sup> data showed a considerable learning effect in the turn. To minimize this learning, the scenarios with different turn buoy configurations were run first. Therefore, this comparison of gated and one-side channel markings is conservative and is not as large as it might have been.

The conclusions to be drawn from this data are that the one-side 1-1/4 nm spaced channel markings are not adequate to result in safe transits because pilots are not provided enough reference points to know with certainty the ship's position in the channel. Also one-side markings encourage a variety of piloting techniques which result in highly variable performance.

### 2.3 EFFECT OF BUOY SPACING ON ONE-SIDE CHANNEL MARKINGS

By comparing the two inside scenarios, one can see the effect of spacing on piloting performance. Scenario 2 has 1-1/4 nm spacing between buoys and scenario 4 has half the space (5/8 nm) between buoys. These scenarios are shown in Figure 10.

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<sup>28</sup>W.R. Bertsche, D.A. Atkins, and M.W. Smith, op. cit.

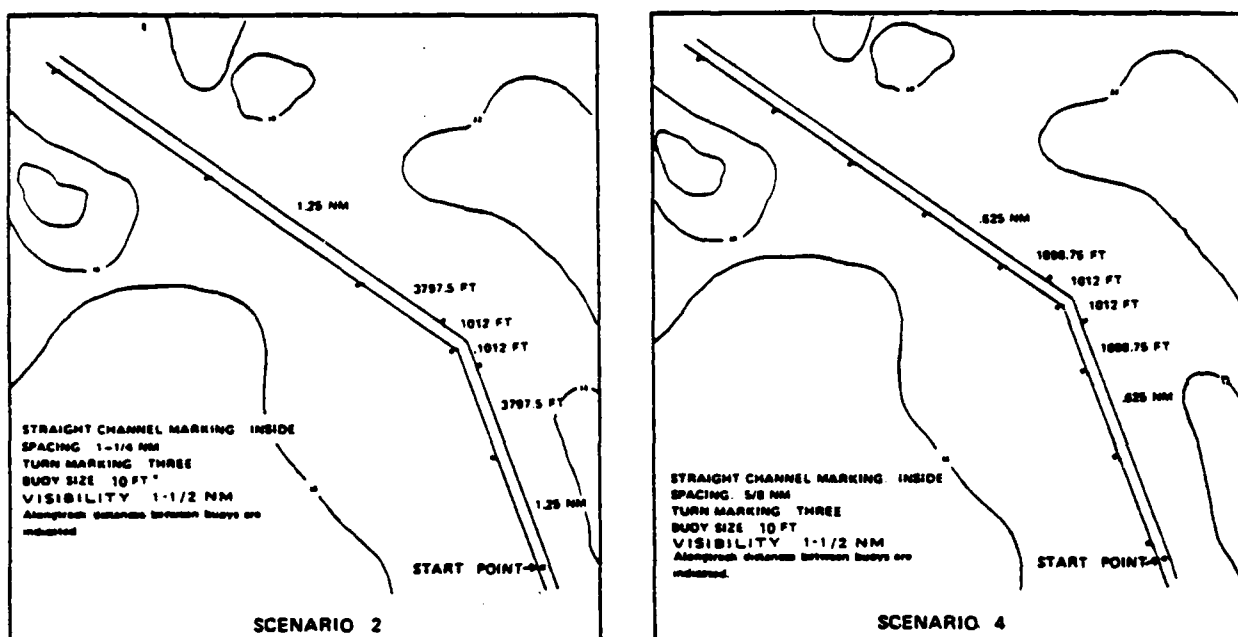


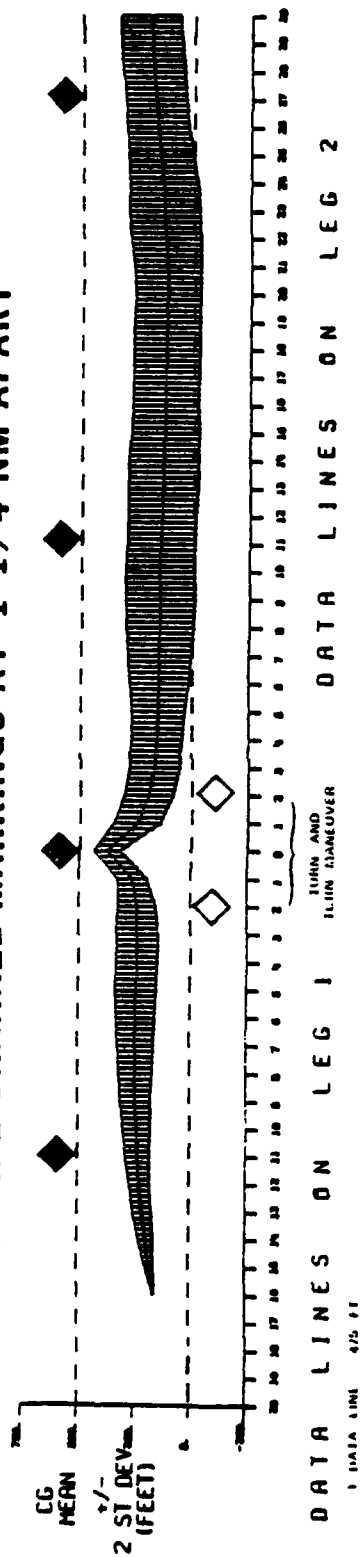
Figure 10. Scenarios 2 and 4

Contrary to pilot opinion and the presimulation hypothesis, shortening the spacing for one-side buoy configurations did not significantly improve performance. Piloting performance differences between the two scenarios is shown in the combined track plots of Figure 11. As can be seen, both configurations result in the track envelope skimming the channel edge, thereby yielding unsafe transits. The shortened spacing resulted in a nonsignificant improvement in the mean and standard deviation. This is further illustrated in Figure 12.

The primary concern with this comparison is the very wide standard deviations resulting from the one-side inside buoy configurations. This indicates that the pilots were unable to determine precise position information and as a result their strategies were not uniform, predictable, or necessarily successful for safe pilotage. This is confirmed by the postsimulation interviews with the pilots. While all pilots agreed that piloting with buoys on one-side was improved by shortened spacing, pilots opinion on actual use and safety of navigation varied. Only half the subjects believed they could safely navigate in a channel marked by one-side buoys in the real world; the other half believed that regardless of spacing, one-side buoys were dangerous.

The pilots' strategies with the greater spaced one-side buoys are discussed in section 2.2. When the spacing was shortened, the pilots appeared to try to determine angular relationships between buoys and to "range" the buoys to see if the buoys were "closing or falling off." Although the additional buoys shortened spacing, they did not substantially improve performance.

# SCENARIO 2: INSIDE CHANNEL MARKINGS AT 1 1/4 NM APART



# SCENARIO 4: INSIDE CHANNEL MARKINGS AT 5/8 NM APART

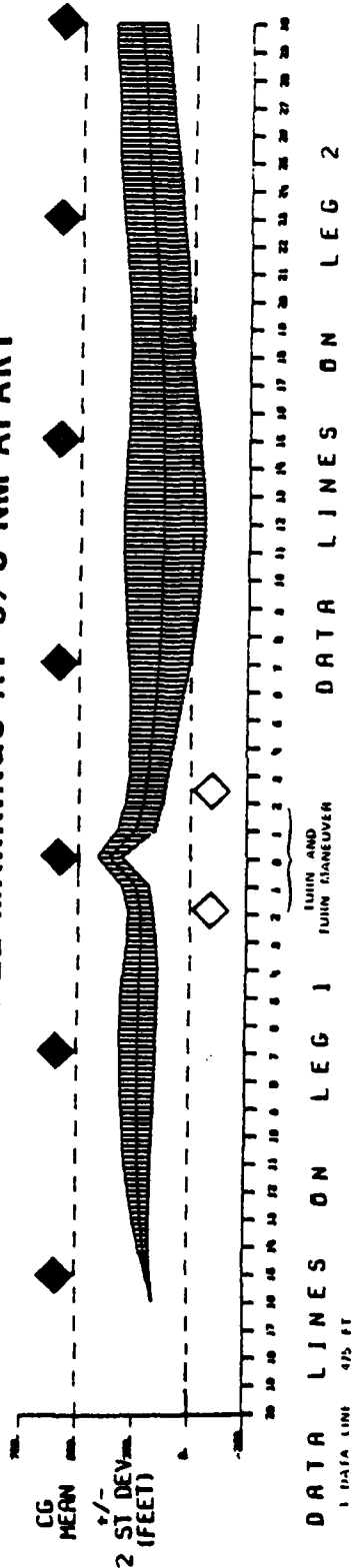


Figure 11. Combined Plots of Piloting Performance of One Side Channel Markings at 5/8 nm Versus 1 1/4 nm Spacing in 1 1/2 nm Visibility

BUOY SPACING WITH ONE-SIDED CONFIGURATIONS

— 1/4 SPACING (SCEN 2)  
 - - - 5/8 SPACING (SCEN 4)

(NO STATISTICAL DIFFERENCE INDICATED AT  
 10 LEVEL OF SIGNIFICANCE)

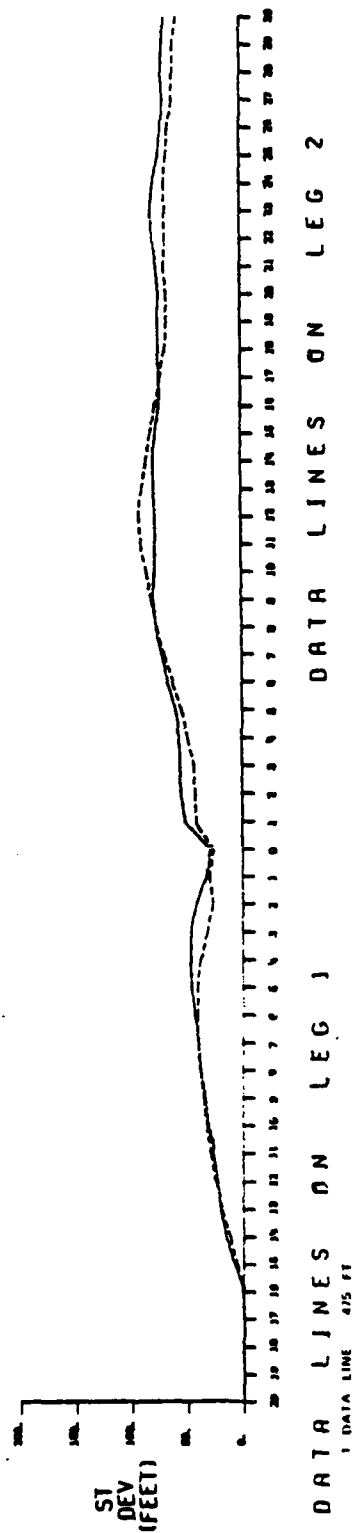
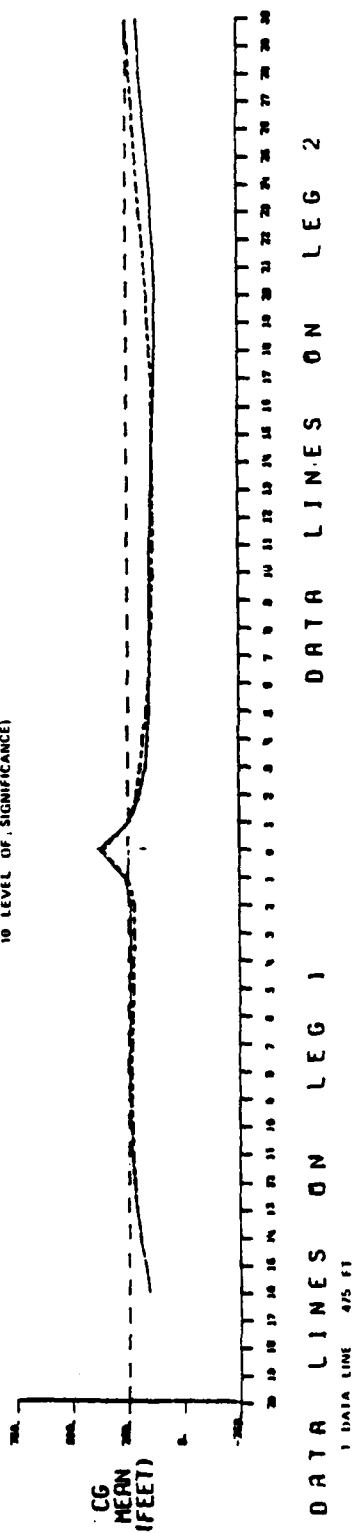


Figure 12. Combined Plots of Piloting Performance for One Side Channel Markings:  
 5/8 nm Versus 1 1/4 nm Spacing in 1 1/2 nm Visibility

The helm orders are shown in Figures 13 and 14. The mean frequency of control activities for scenario 2 is 12 rudder commands, 12 course commands, and 0 engine orders. For scenario 4 the mean frequency of control activities is 13 rudder commands, 9 course commands, and 1 engine order. The increased course commands for scenario 2 (longer spacing) does not indicate more controllability, but rather more guessing to assess position. In scenario 2 several pilots tried to compensate for lack of piloting cues (buoys) by using the ship as a steering instrument. The pilots periodically steered the leg course to assess the ship position, then altered course accordingly.

Because of the uncertainty of ship position, pilots found it difficult to steady up in leg 2 even as the wind and current effects decrease toward the end of the transit. In scenario 2 three pilots never steadied the ship on the centerline, and in scenario 4 two pilots could never find the centerline.

This data again illustrates the inadequacy of one-side buoys. If buoy density is to be increased instead of adding more one-side buoys, gated buoys are the more advantageous arrangement. This is further discussed below.

#### 2.4 EFFECT OF ALTERNATIVE STRAIGHT CHANNEL MARKINGS WITH EQUAL BUOY DENSITIES

Given the same number of buoys to mark a channel, 75 percent of the pilots preferred long-spaced gated buoys to the shorter spaced one-side buoys in 1-1/2 nm visibility. Those pilots who preferred one-side markings with closer spacing believed it is more beneficial to be able to compare the ship's position more frequently to a buoy. The scenarios are shown below by Figure 15. The buoys in scenario 1 are gated and spaced 1-1/2 nm apart. The buoys in scenarios 4 and 5 are only on one side; however, since the number of buoys marking the channel are equal, buoy spacing under one-side conditions are 5/8 nm apart.

The pilots believed their prior experience in the channel (the familiarization run plus two gated scenarios) made piloting with one-sided buoy markings more feasible since in piloting familiarity with the channel is essential. Surprisingly, when choosing between one-side channel markings half the pilots preferred inside markings and half preferred outside markings for the given conditions. Two pilots would not choose since they believed that one-side buoys were unsafe under any conditions. Reasons given for choosing inside buoy markings were (1) the turn and the current were from the left so that area was most critical and should be marked, (2) because left compensation was necessary for crabbing of the ship, and (3) that outside buoys were difficult to work with. Reasons for pilots preferring outside channel markings were (1) with the current and wind there is a strong tendency to be carried to the outside of the leg, and (2) red buoys are easier to see.

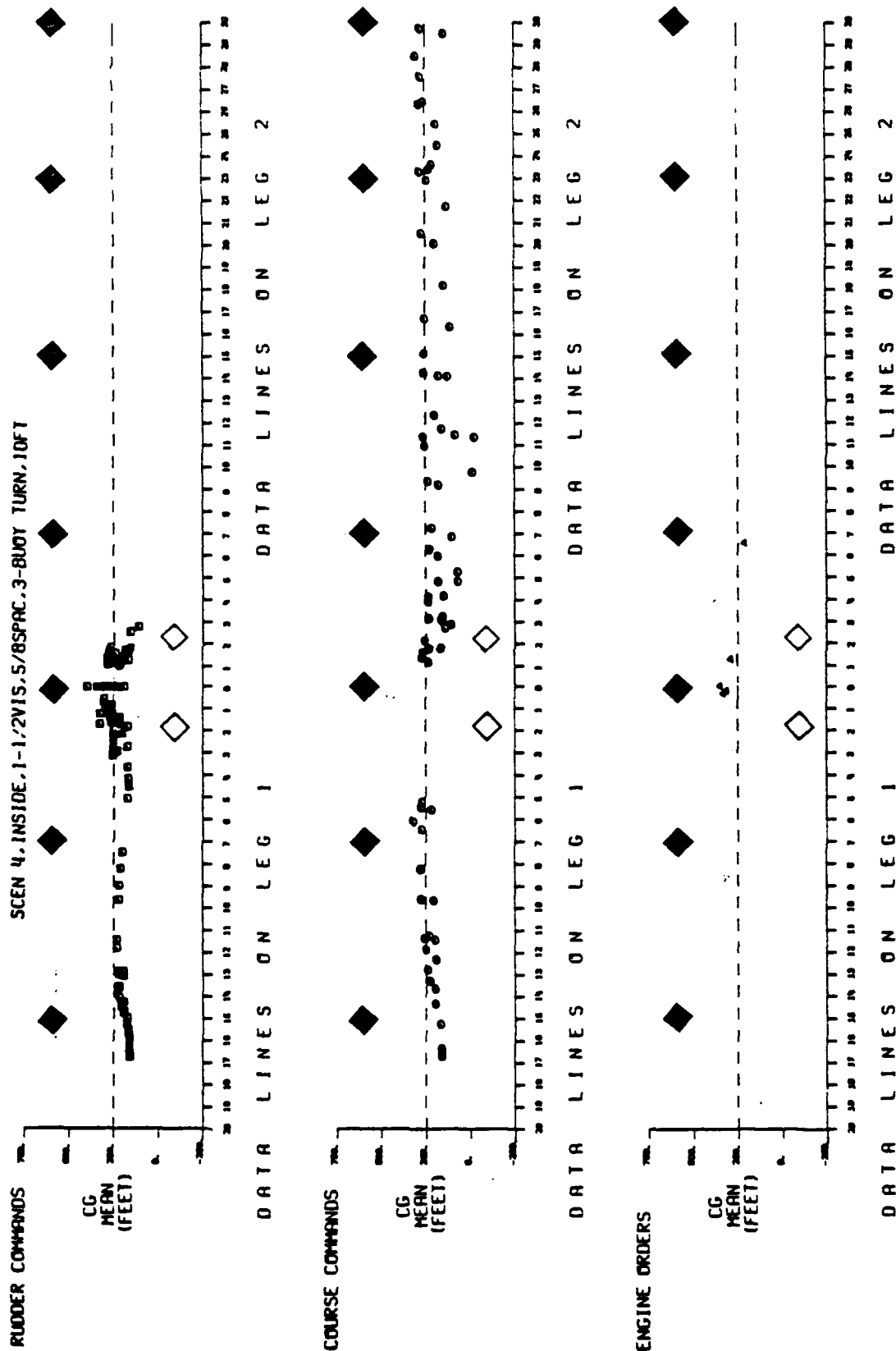


Figure 13. Helm Orders for Scenario 2

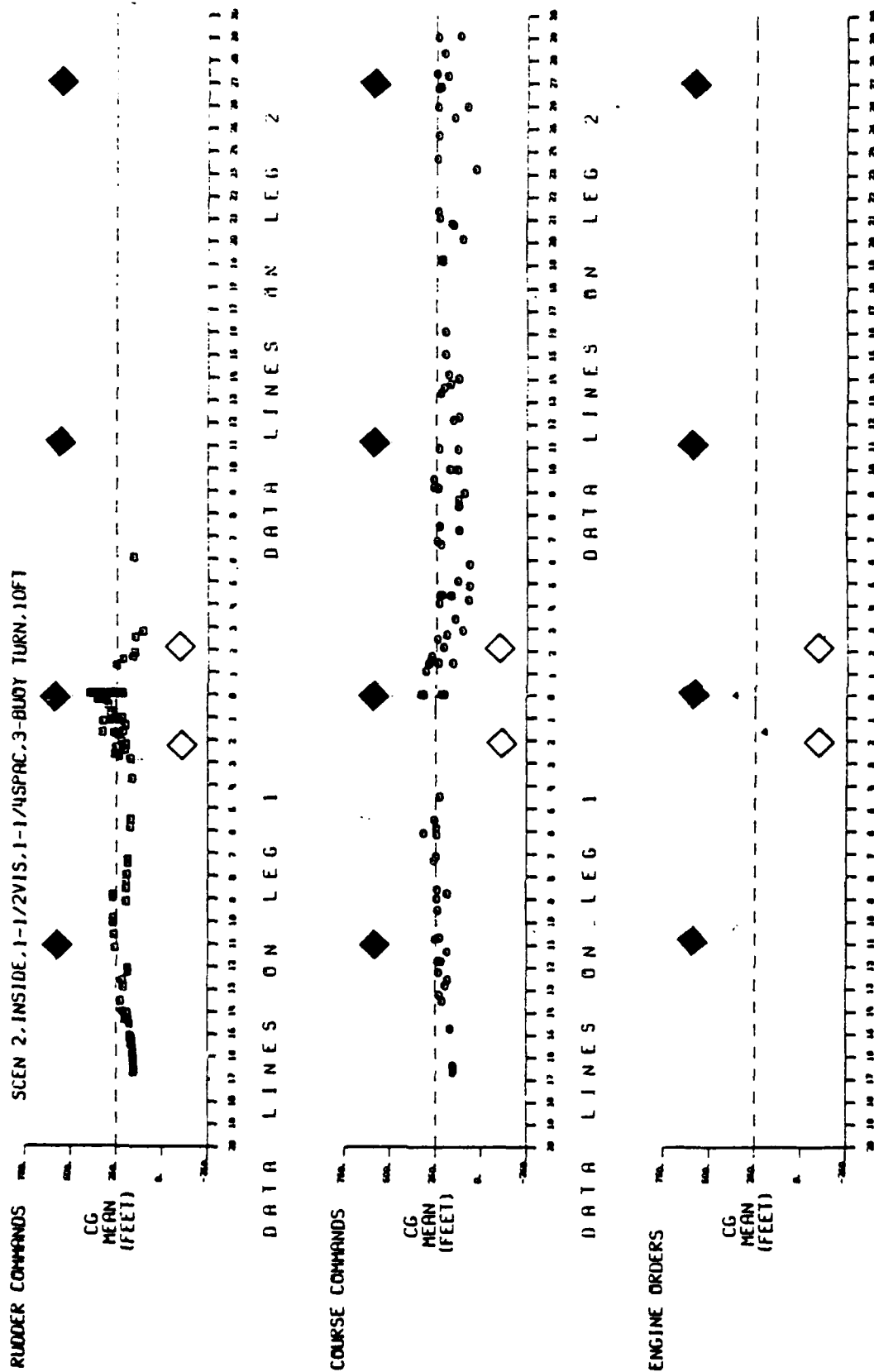


Figure 14. Helm Orders for Scenario 4

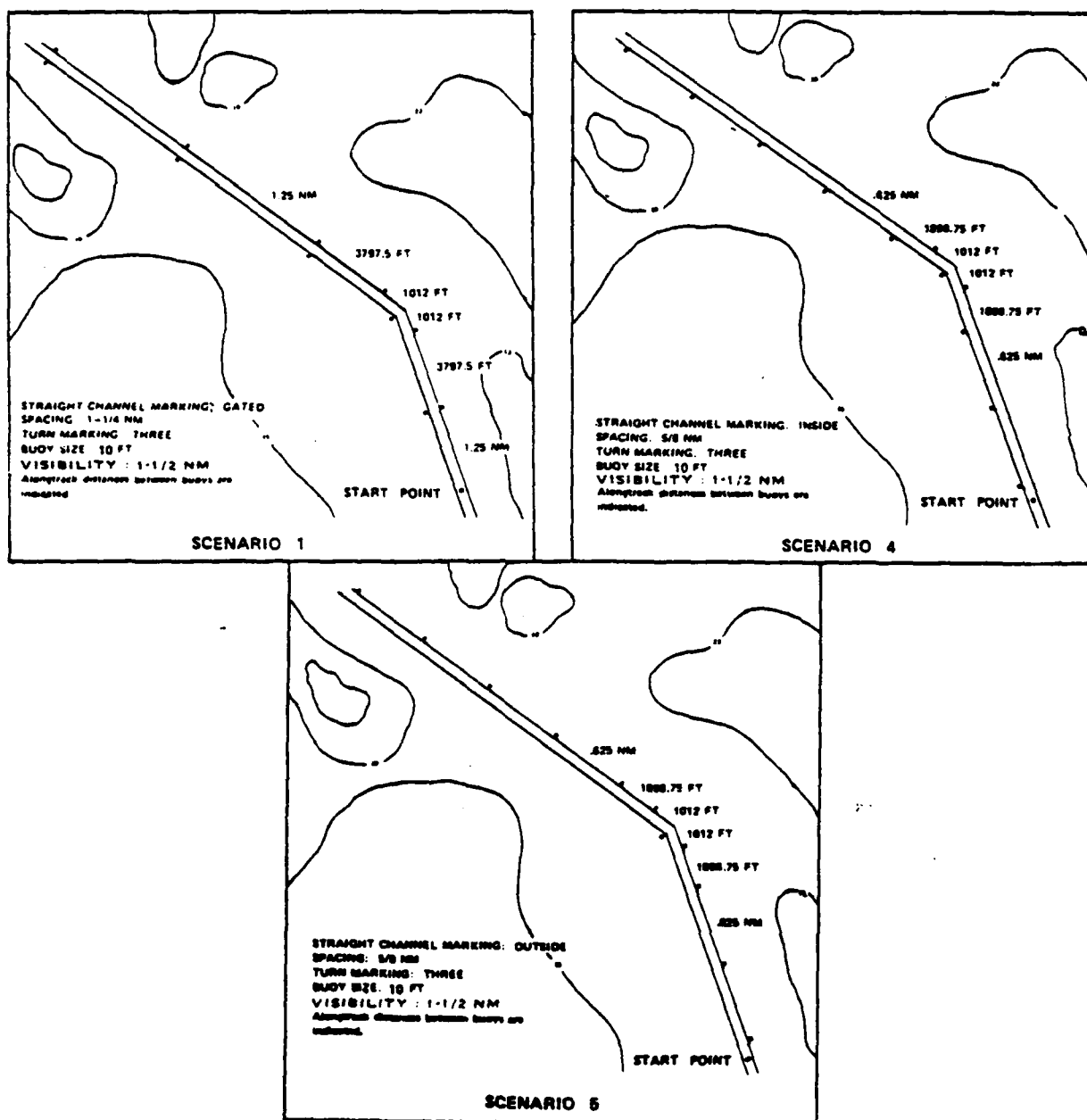


Figure 15. Scenarios 1, 4, and 5

Pilot performance in each of these conditions is shown by Figure 16. Scenario 1 with gated buoys is the baseline scenario which has appeared in the CAORF and Channel Width experiments.<sup>29,30</sup> The 1-1/4 nm spacing was selected because these earlier experiments showed that this spacing was adequate with gates: 5/8 nm spacing did not substantially improve performance. To evaluate performance, each equal density one-side scenario will be compared first to scenario 1 and then to each other.

The hypotheses, taken from the presimulation reports,<sup>31</sup> for the effect of alternative straight channel marking are as follows. In leg 1 the gated condition will show the mean closest to the centerline and the smallest standard deviation. The mean for each one-sided condition will favor that side and both will show a larger standard deviation than the gated conditions. In leg 2 the condition with buoys to the inside of the turn and upcurrent (scenario 4) will show the most upcurrent mean, probably closer to the centerline than the gated condition (scenario 1); while the condition with buoys to the outside of the turn and downcurrent (scenario 5) will show a mean furthest downcurrent and furthest from the centerline. The gated condition will show the smallest standard deviation.

As shown in Figure 16, long spaced gated buoys did result in the mean track close to the center of the channel and a smaller standard deviation. Performance, however, in the one-side scenarios was not as predicted. With the inside channel marking, tracks did not tend to hug buoys as was expected but instead were over to the right side of the channel. Trackkeeping after the turn was hampered by lack of buoys to judge the starboard channel boundaries. This resulted in the inability to recover from the turn and compensate for crosswind and crosscurrent conditions. Performance with outside markings was better than with inside markings. When using the outside buoys, pilots worked harder to stay off the buoys to compensate for current. The large standard deviation suggests lack of agreement and/or uncertainty as to where the ship or the centerline is located.

When comparing inside buoys to outside buoys, the outside buoys were better because the inside buoys failed to adequately mark the area to recover from the turn while the outside buoys were acceptable. With outside buoys, the pilots avoided being set into the buoys by the current and this kept them in the channel. In terms of the piloting task, avoidance of the set of the current was more important than knowing what course to steer to come out of the turn. This is opposite the presimulation prediction.

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<sup>29</sup>M.W. Smith and W.R. Bertsche, op. cit., August 1980.

<sup>30</sup>M.W. Smith and W.R. Bertsche, op. cit., January 1981.

<sup>31</sup>M.W. Smith, op. cit.

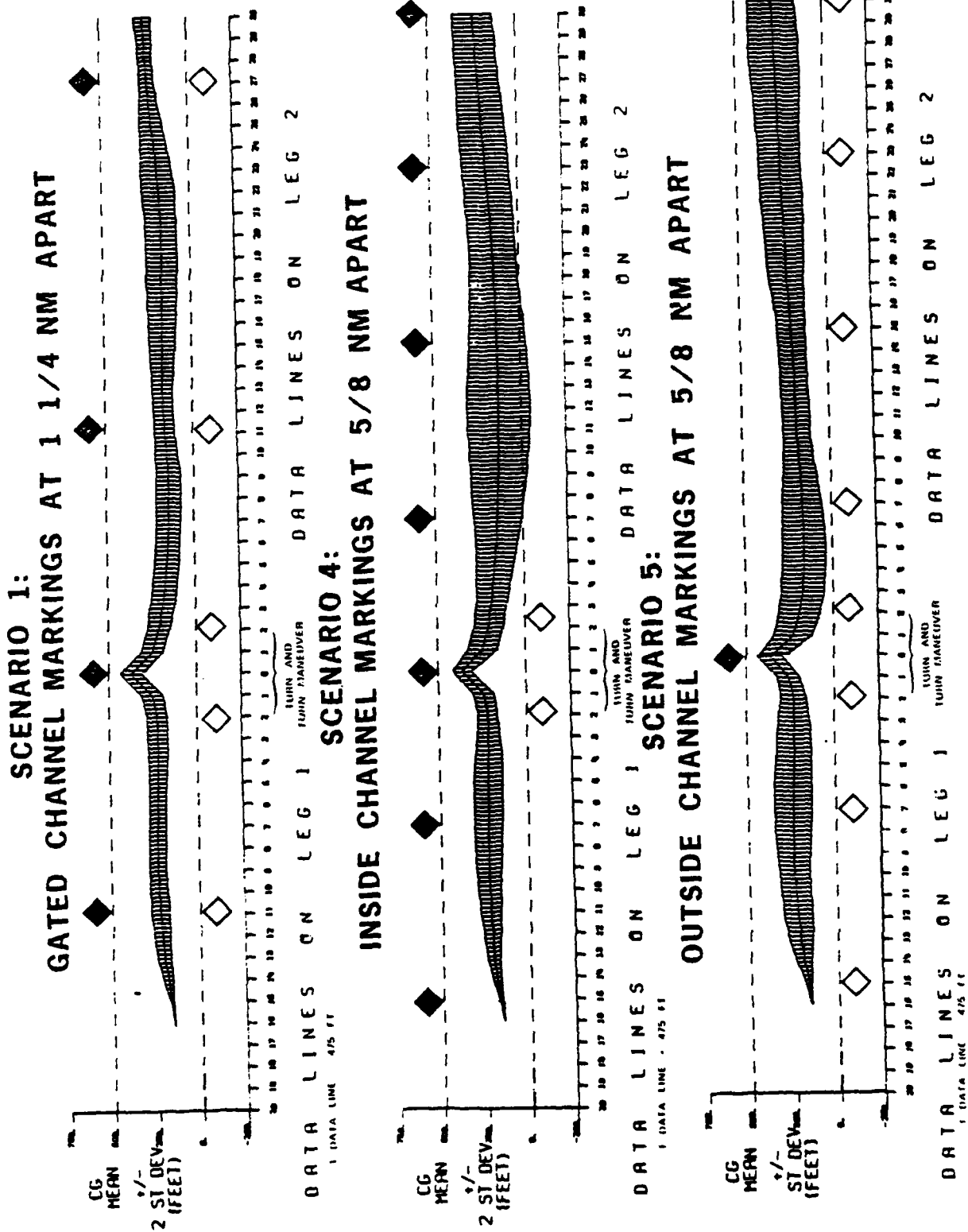


Figure 16. Combined Plots of Piloting Performance for Equal Buoy Densities:  
Gated 1 1/4 nm Spaced Buoys Versus One Side 5/8 nm Spaced Buoys in 1 1/2 nm Visibility

It is interesting to note that in this project pilots have never hit a buoy so buoy placement controls tracks. In looking at Figure 16 it appears that buoys marking the outside boundaries between data lines 1 and 11 are essential to keep tracks inside the channel with the given turn, wind, and current. Failure with inside channel markings occurs after passing the third turn buoy with no additional buoy marking the outside boundary. As the wind and current effect dies, controllability improves and all tracks are in the channel.

A detailed comparison of the alternative channel markings in both mean crosstrack location and standard deviation is shown by Figures 17, 18, and 19. Figure 17 compares gates to inside markings, Figure 18 compares gates to outside markings, and Figure 19 compares the one-side markings. The differences in performance will be discussed by region.

Region 1 covers the activity occurring in leg 1. Here the pilots were instructed to return to and steady up on the centerline. The mean and standard deviation of the distance required to return to the centerline, the overshoot following the turn, and the distance to steady up in leg 1 is shown in Table 6.

As is seen the only significant difference occurs in the overshoot standard deviation. While the means are close, the dispersion of tracks is high for one-side buoys particularly the outside markings. The gated buoys tend to keep individual tracks more homogeneous thereby keeping the average standard deviation low.

Since the turns in all three scenarios were marked by the same buoy configuration, any difference in turn performance would be due to ship position at turn initialization. This position was a result of information acquired by straight channel marking. As seen by region 2 data performance in scenarios 1 and 4 was similar due to available channel boundary information for better turn initialization position. No such complete information was available for the outside buoy scenario. This resulted in the widest standard deviation throughout the turn (see Figure 20). This was only significant when comparing it to the baseline gated scenario. Since there are no real differences of means the turns were initiated at approximately the same alongtrack position, it was the crosstrack position that was different. The implication for turn designs is that it is imperative to have enough buoys to provide information to determine exact crosstrack and alongtrack position to set up for the turn.

The turn recovery and initial maneuvering in a crosscurrent and wind are shown in region 3. Region 4 shows the steady up in Leg 2 as wind and current diminish. The crosstrack information for pertinent data lines is described in Table 7.

The most obvious difference between tracks in region 3 is the large standard deviation occurring in scenario 4 (inside marking). Here trackkeeping was hampered by the lack of downcurrent buoys to aid pilots in correcting for the set to steady up in leg 2. The pilots were unable

# EFFECT OF STRAIGHT CHANNEL MARKING WITH EQUAL DENSITY

— SCEN 1, GATED, 1 1/2 VIS, 3-BUOY TURN  
 - - - SCEN 4, INSIDE, 1 1/2 VIS, 3-BUOY TURN

10, 5, - AREAS WHERE THE PROBABILITY OF DIFFERENCE  
 OCCURRING BY CHANCE IS LESS THAN 10%

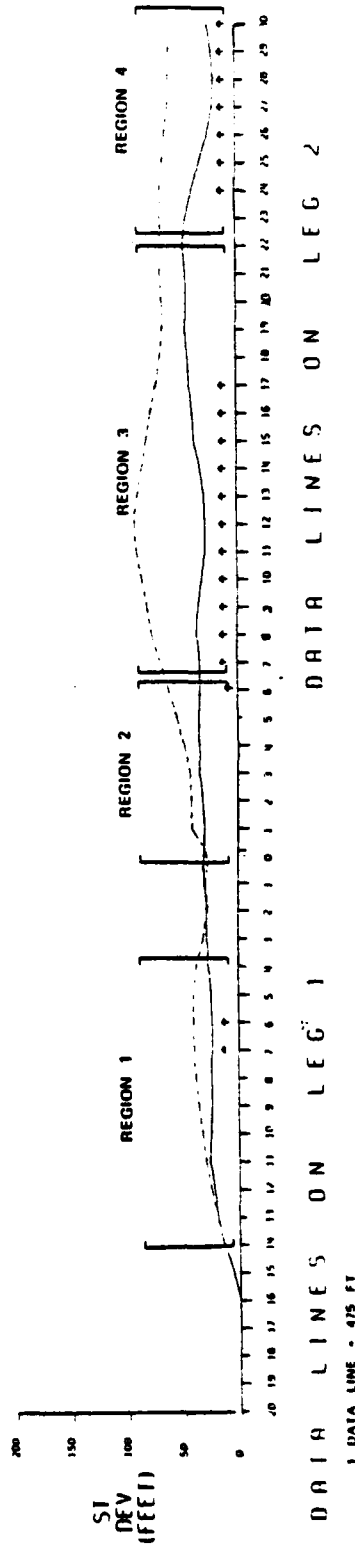
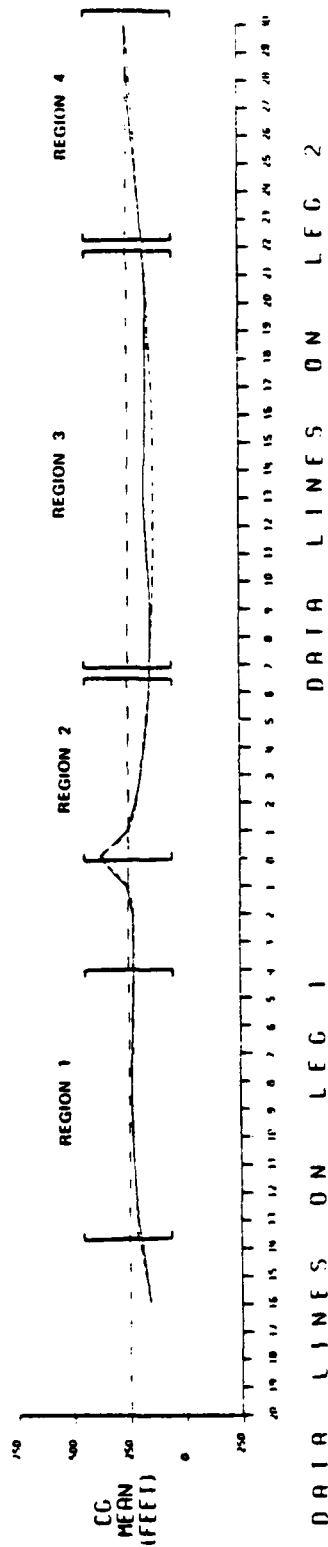
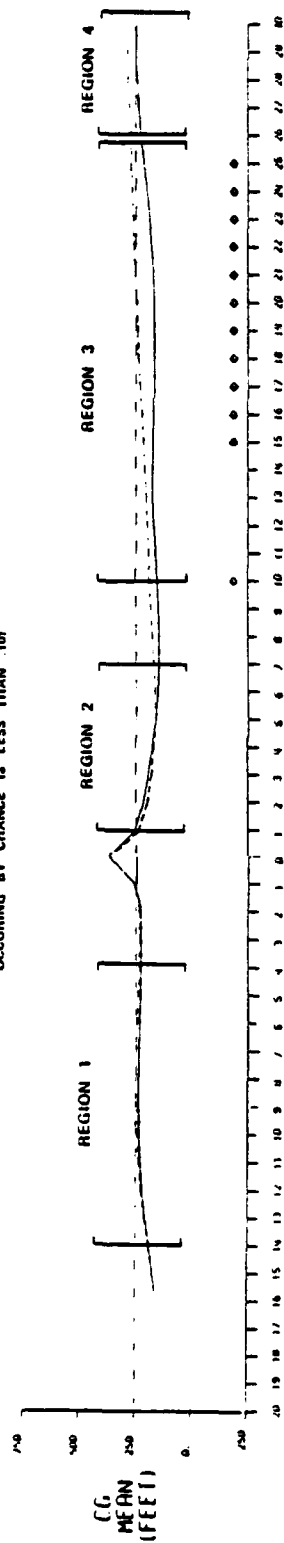


Figure 17. Crosstrack Mean and Standard Deviation of Piloting Performance for Equal Density Arrangements: Gated Versus Inside at 1 1/2 nm Visibility

EFFECT OF STRAIGHT CHANNEL MARKING WITH EQUAL DENSITY

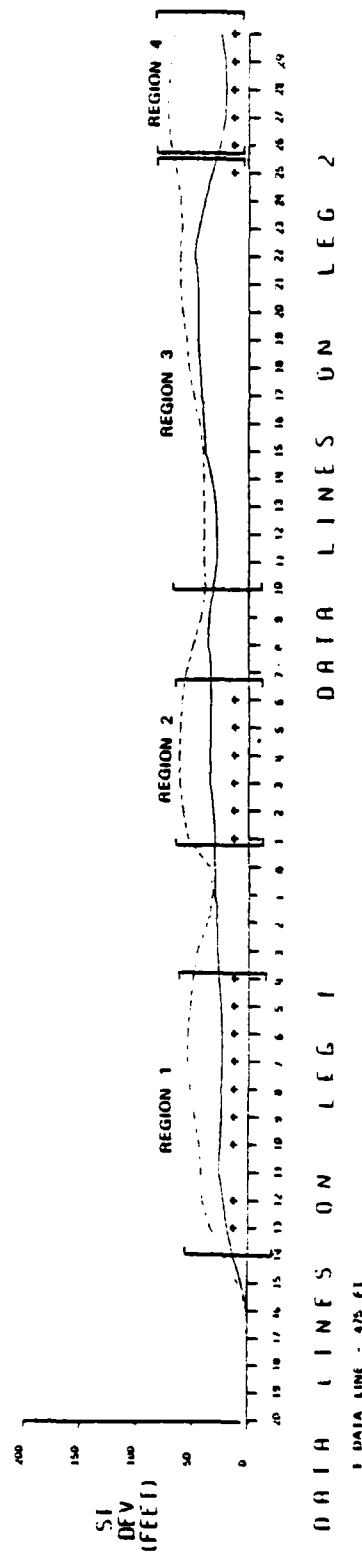
— SCEN 1, GATED, 1-1/2 VIS, 3-BUOY TURN  
 --- SCEN 5, OUTSIDE, 1-1/2 VIS, 3-BUOY TURN

(O, X, \* AREAS WHERE THE PROBABILITY OF DIFFERENCE OCCURRING BY CHANCE IS LESS THAN .10)



DATA LINES ON LEG 1 DATA LINES ON LEG 2

1 DATA LINE = 475 FT



DATA LINES ON LEG 1 DATA LINES ON LEG 2

1 DATA LINE = 475 FT

Figure 18. Crosstrack Mean and Standard Deviation of Piloting Performance for Equal Density Arrangements: Gated Versus Outside at 1 1/2 nm Visibility

EFFECT OF STRAIGHT CHANNEL MARKING WITH EQUAL SPACING

— SCEN 4, INSIDE, 1 1/2 VIS, 3-BUOY TURN

- - - SCEN 5, OUTSIDE, 1 1/2 VIS, 3-BUOY TURN

10, 9, - AREAS WHERE THE PROBABILITY OF DIFFERENCE  
OCCURRING BY CHANCE IS LESS THAN .100

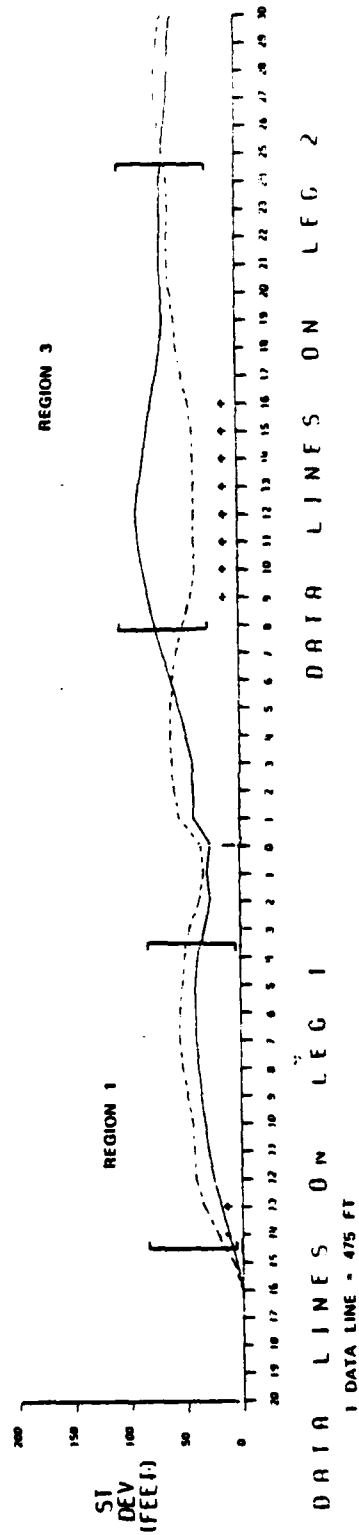
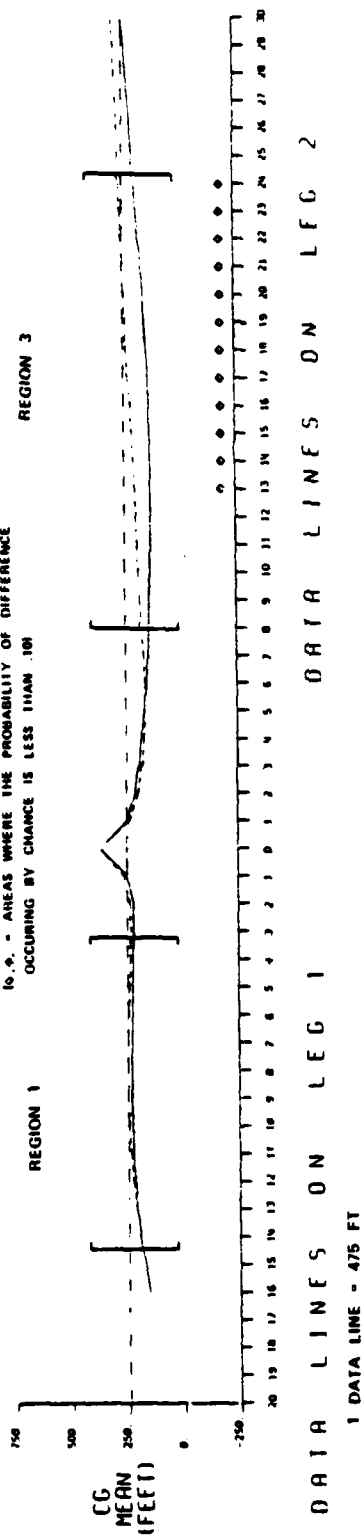


Figure 19. Crosstrack Mean and Standard Deviation of Piloting Performance for Equal Density Arrangements: Inside Versus Outside at 1 1/2 nm Visibility

ONE SIDE  
OUTSIDE

ONE SIDE  
INSIDE

GATED

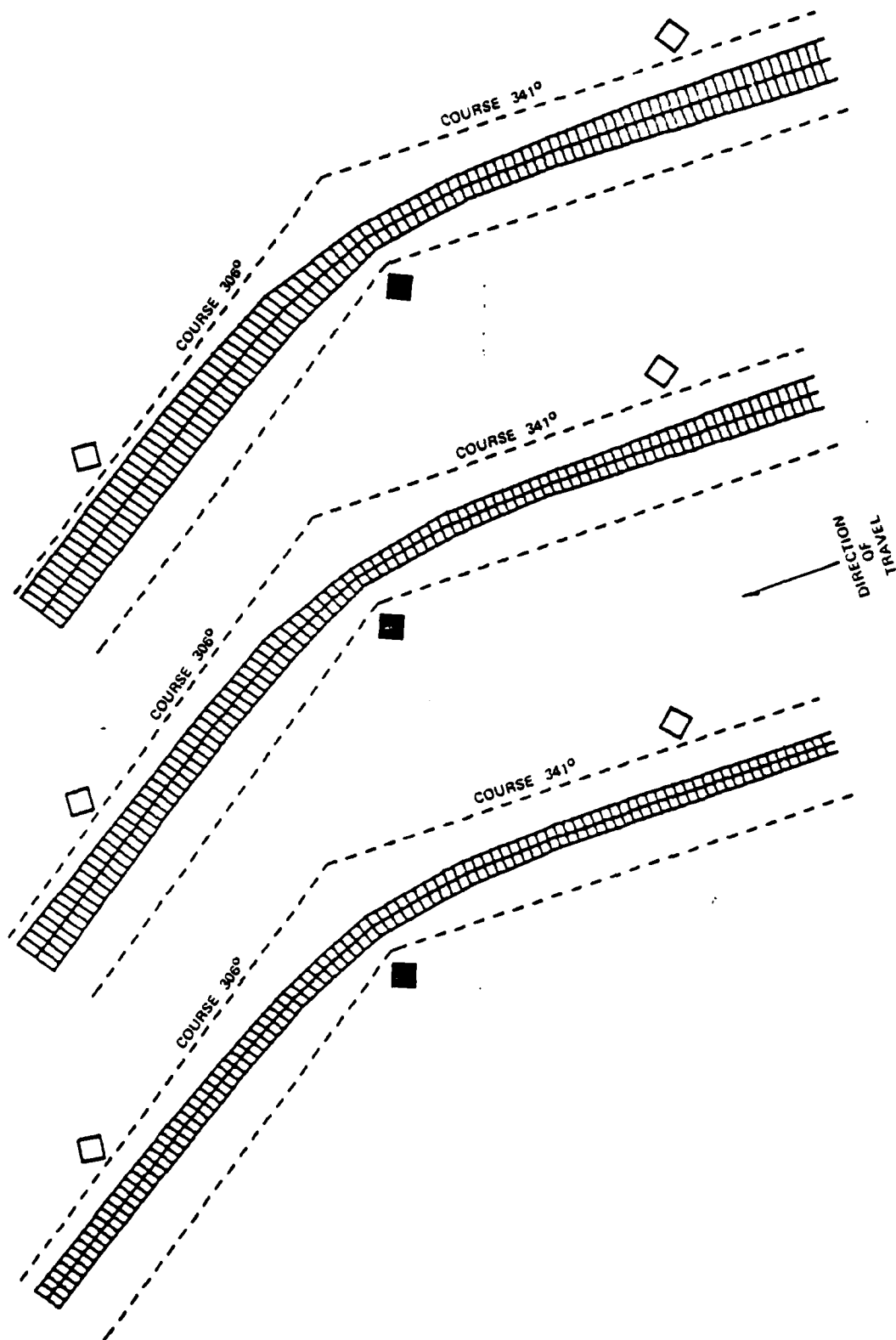


Figure 20. Turn Performance for Equal Buoy Density Arrangements

TABLE 6. MANEUVERING ANALYSIS - RETURN TO  
AND STEADY UP ON CENTERLINE FOR REGION 1

GROUP MEAN			
Performance Measure	Gated (Scenario 1)	Inside (Scenario 4)	Outside (Scenario 5)
Distance to return to centerline (feet before turn)	5043	5225	5225
Overshoot following return to centerline (feet away from centerline)	21.7R	22.6R	3.5R
Distance to steady up in Leg 1 (feet before turn)	4739	4557	3342
STANDARD DEVIATION			
Performance Measure	Gated (Scenario 1)	Inside (Scenario 4)	Outside (Scenario 5)
Distance to return to centerline (feet before turn)	972	790	972
Overshoot following return to centerline (feet away from centerline)	24.8*	41.2*	54.8*
Distance to steady up in Leg 1 (feet before turn)	972	1337	1580
R = Right of Centerline *Probability less than .10 of occurring by chance			

TABLE 7. MANEUVERING ANALYSIS - CROSSTRACK  
PERFORMANCE DATA FOR REGIONS 3 and 4

MAXIMUM MEAN CROSSTRACK POSITION			
	Gated (Scenario 1)	Inside (Scenario 4)	Outside (Scenario 5)
Region 3 (feet)	96.4R	120.9R	61.7R*
Region 4 (feet)	38.4R	45.8R	42.7L*
MAXIMUM CROSSTRACK STANDARD DEVIATION			
	Gated (Scenario 1)	Inside (Scenario 4)	Outside (Scenario 5)
Region 3 (feet)	45.6	91.6*	58.8
Region 4 (feet)	32.7*	65.6	72.2
R = Right of Centerline L = Left of Centerline *Probability less than .10 of occurring by chance			

to judge their crosstrack position correctly and some could not stay in the channel. In a narrow channel with strong wind and current, it is necessary for a buoy to be placed in the region between data lines 7 and 11 to the outside of the turn to ensure pilots have control over the ship's set in recovering from the turn. In this recovery, the standard deviation is more than double the gated or outside scenarios, and this causes concern over the adequacy of the buoy configuration. This large standard deviation shows lack of agreement in strategies to recover from the turn and uncertainty of ship position as well as centerline location.

The outside buoys are adequate for entering a second leg from a sharp turn with a strong crosscurrent and wind on the port quarter. Pilots succeed in the transiting safely down leg 2 due to the dominant strategy of avoiding being set into the buoys. However, since the standard deviation does not decrease as wind and current effects diminish supports the contention that pilots were merely avoiding buoys; the wind and current not pilot performance was the cause of the satisfactory tracks in region 3. The increase in dispersion of tracks under "near perfect environmental conditions" shows confusion and uncertainty in judging the ship's position.

In summary, given an equal density of buoys, long-spaced gated buoys is the superior buoy configuration over short-spaced buoys placed either to the inside or outside of the turn when visibility is longer than spacing. If one-side buoys are to be used, environmental factors must be carefully evaluated to ensure safe piloting performance. Further, data indicate that, as a minimum, buoys immediately following a turn should be located to the outside of the turn.

### Section 3

#### PERFORMANCE AS A FUNCTION OF VISIBILITY

##### 3.1 OVERVIEW

A one-side scenario and a staggered scenario were run under 3/4 nm visibility to determine differences in piloting performance both as a function of visibility and configuration. The one-side scenario run at 3/4 nm was compared to the same scenario run at 1-1/2 nm visibility and was also compared to the staggered scenario run at the lower visibility. The two scenarios run under 3/4 nm visibility had a buoy marking every 5/8 nm, therefore, except while near the turn, only one buoy could be seen at a time. However, the one-side buoy scenario had alongtrack spacing of 5/8 nm and the staggered scenario had alongtrack spacing at 1-1/4 nm due to buoy markings alternating from one side of the boundary to the other. The comparison between these scenarios will evaluate pilot performance with buoys marking one side versus buoys which mark both sides of the channel.

The one-side scenario with limited 3/4 nm visibility had better results than when visibility was increased to 1-1/2 nm. This was due to limited information decreasing pilotage options so pilots were more conservative and strategies were similar. Piloting performance was also better when using the staggered buoys in 3/4 nm visibility than when using one-side buoys in 1-1/2 nm visibility. Therefore, with an equal density of buoys, gated buoys are better than one-side configurations under good visibility and staggered buoys are better than one-side configurations when visibility is poor. (The previous CAORF experiment had shown staggered buoys to be better than gated buoys of equal density when visibility is poor.)

##### 3.2 THE SCENARIOS

This set of scenarios was developed to evaluate the effectiveness of one-side buoy configurations in competing with other buoy configurations under low visibility. The scenarios are shown below by Figure 21. Scenario 8 is identical to scenario 4 but with lower visibility (3/4 nm versus 1-1/2 nm). Scenario 9 is a staggered version of scenarios 4 and 8. The dimensions show that all alongtrack buoy positions are the same. The spacing for the staggered configuration differs from previous experiments since the first staggered buoy is located 1898.75 feet from the turn buoy while this dimension was 3797.5 feet (1/2 the buoy spacing) in all previous experiments. The staggered condition here is also different from all previously studied staggered configurations since the first buoy following the turnmarking is to the inside. This new staggered marking was developed to be compatible with scenarios 4 and 8 to ensure no bias against the staggered or one-side scenarios existed. With visibility at 3/4 nm and buoy-to-buoy spacing 5/8 nm apart, only one buoy is seen except when approaching the turn.

The staggered and one-side scenarios have the same buoy densities marking the channel but have different alongtrack spacing for each

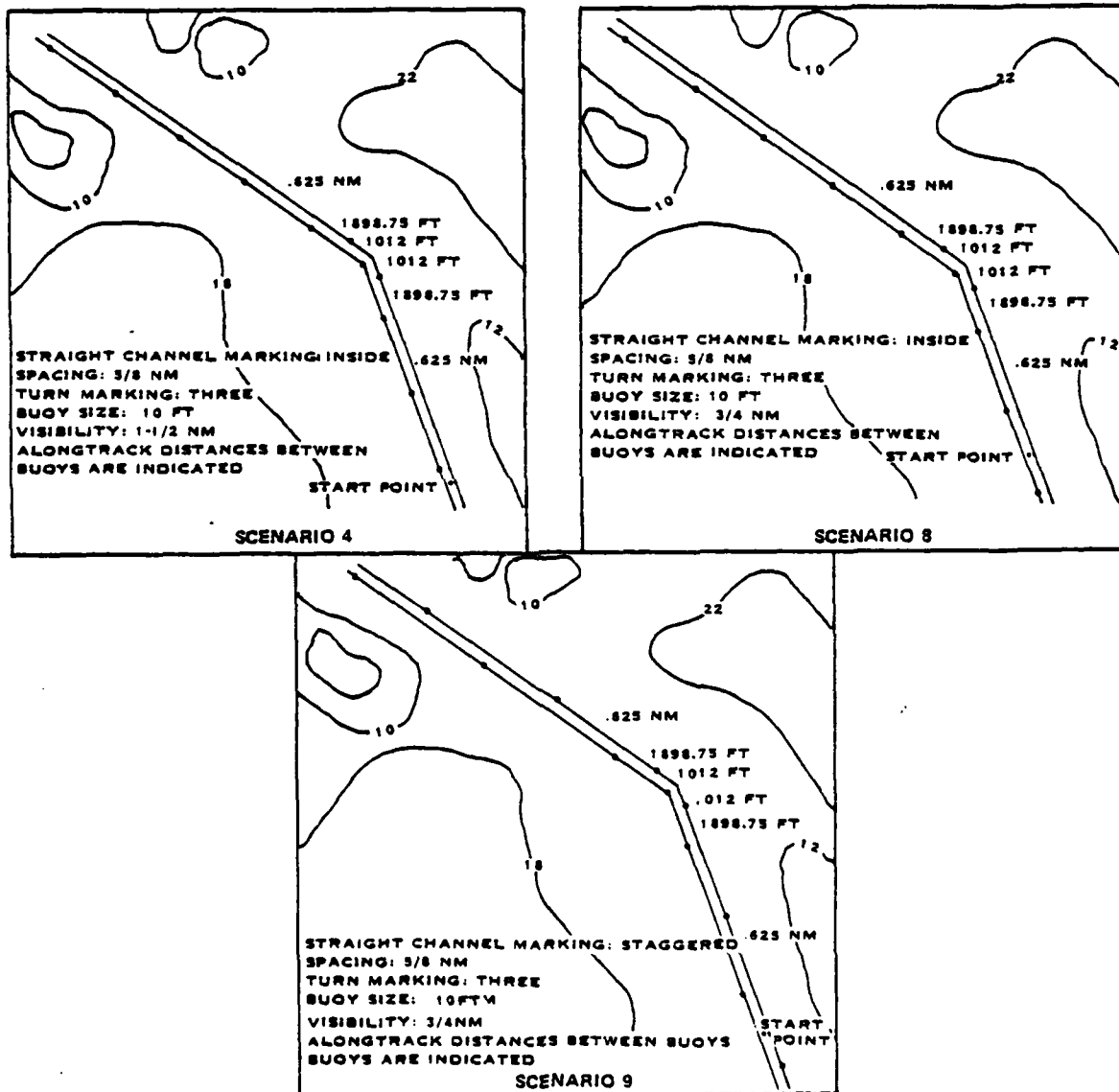


Figure 21. Scenarios 4, 8, and 9

channel boundary. It was hypothesized that with poor visibility in one-way channels, the one-side markings might result in lower crosstrack standard deviation with more controlled tracks as a function of the shorter spacing along the channel boundary. Piloting performance differences between the three scenarios is shown in the combined track plots in Figure 22. As can be seen, the staggered channel markings result in superior performance when compared to the one-side scenarios. Also, it appears that piloting performance was better in 3/4 nm visibility than in 1-1/2 nm visibility. Section 3.3 discusses the effect of visibility on piloting performance with one-side markings, and section 3.4 discusses the effect of buoy configuration under limited visibility.

### 3.3 EFFECT OF VISIBILITY ON PILOTING PERFORMANCE WITH ONE-SIDE MARKINGS

On the postsimulation questionnaire, all pilots agreed that their tracks were improved when piloting in increased visibility using inside channel markings. This was because the pilots could "see more instead of feeling to one buoy and hoping the next buoy would show up in a comfortable place." Figure 23, however, shows this is not to be true. Short visibility resulted in better performance than long visibility. Figure 23 shows this is not significant when comparing mean tracks, but it is significant when comparing the standard deviations. A similar effect was also observed in the CAORF experiment<sup>32</sup> where performance with staggered buoys spaced 5/8 nm apart was better in 3/4 nm visibility than 1-1/2 nm visibility.

An explanation for this effect is that in longer visibility pilots have more options. They can either steer toward the most distant buoy or a close buoy so there is less agreement on exactly what heading to steer. Under shorter visibility conditions pilots see fewer buoys so they tend to stay closer to the buoys they can see. Because of limited information, they are forced to use the "distance off the buoy" method to determine ship position and heading to steer. With fewer options available, strategies tend to become more similar and standard deviation decreases.

It is not reasonable to say short visibility will improve performance. What can be concluded is that less information decreases piloting options so strategies tend to be similar. As seen from prior experiments, lower standard deviation can be associated with limited information.

### 3.4 EFFECT OF BUOY CONFIGURATION UNDER LIMITED VISIBILITY

In limited visibility, staggered buoys resulted in superior performance when compared to one-side buoys. On the presimulation questionnaire most pilots preferred the staggered to one-side buoys because the full width of the channel was marked. They believed they were more likely to stay at the center if the boundaries were

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<sup>32</sup>M.W. Smith and W.R. Bertsche, op. cit., August 1980.

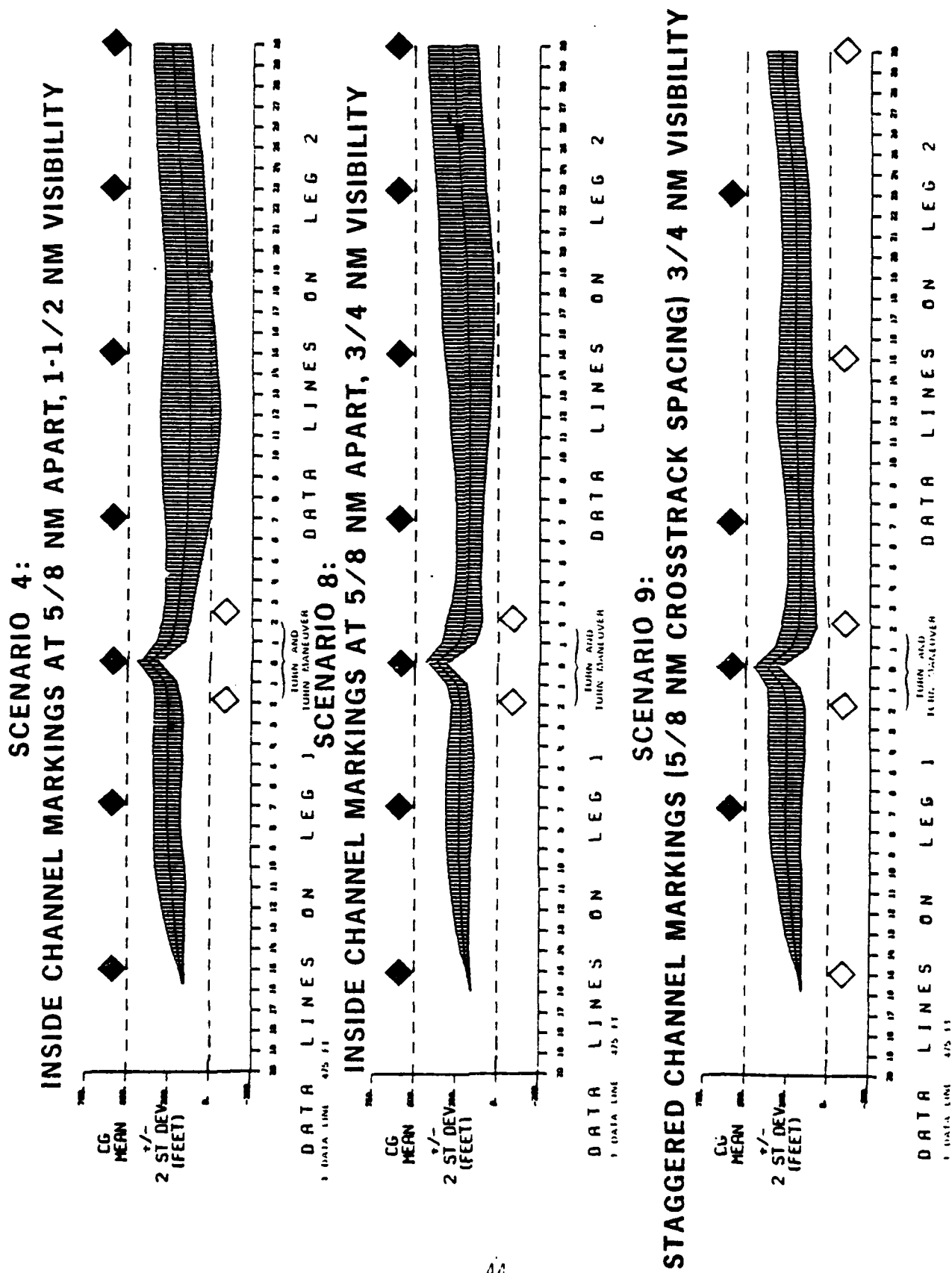


Figure 22. Combined Plots of Piloting Performance Under 3/4 nm Visibility Versus 1 1/2 nm Visibility

# EFFECT OF VISIBILITY ON ONESIDED CONFIGURATION

— 3/4 NM VISIBILITY  
 - - - 1 1/2 NM VISIBILITY

(0.1) - AREAS WHERE THE PROBABILITY OF DIFFERENCE  
 OCCURRING BY CHANCE IS LESS THAN 100

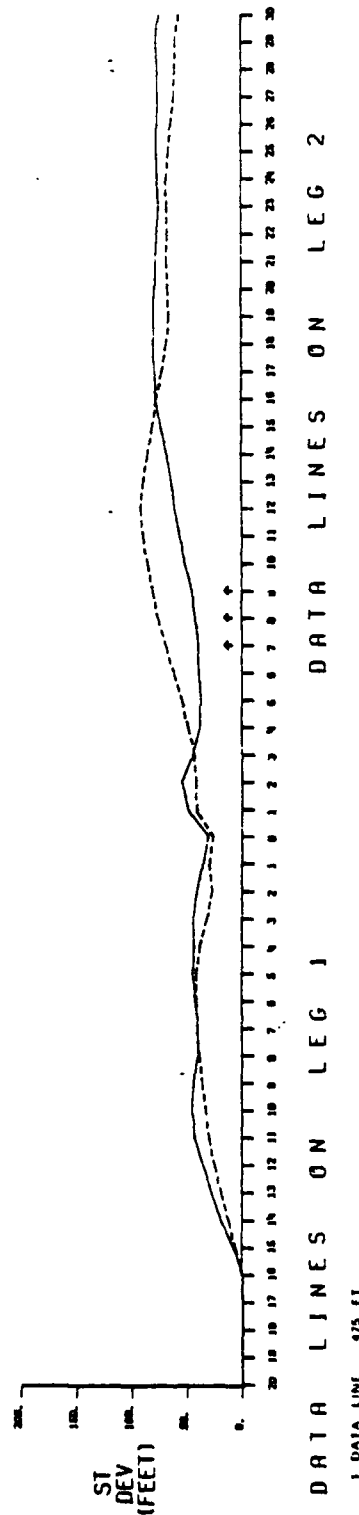
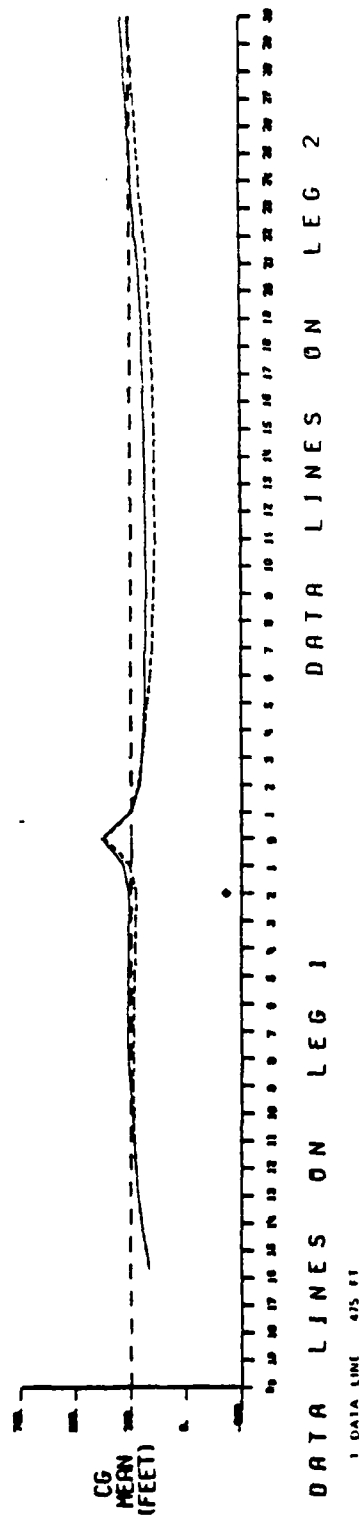


Figure 23. Crosstrack Mean and Standard Deviation of Piloting Performance  
 for Varying Visibility: 3/4 nm Versus 1 1/2 nm

identifiable. The strategy used was to "take shape on the buoy by taking a fix on the visible buoy and maintaining that fix until the next buoy became visible while estimating position within the channel in relation to the buoy that was visible." In limited visibility, pilots said they would look aft to further identify position with more buoys visible. However, several subjects preferred one-side buoys under limited visibility conditions because the closer one-side spacing provided more continuity for "distance-off" cues. These pilots believed that with more regular spacing, it was easier to gauge position so the course (track) would be steadier. The data do not support their position since the one-side standard deviations were higher.

A statistical comparison of the two conditions in both mean crosstrack location and standard deviation is shown in Figure 24. Since crosstrack aids were available on both sides in the staggered configuration, pilots could accurately judge their position and find the centerline. There are no differences between the means of the scenarios, but the smaller deviation shows that pilots were certain of ship positions and could maneuver the ship comfortably.

Pilot performance was better when using the staggered buoys in 3/4 nm visibility than when using one-side buoys in improved 1-1/2 nm visibility (see Figure 22). Even when comparing staggered markings to the best one-side configuration (the outside buoys spaced 1-1/4 nm apart, see Figure 16), the staggered configuration has less standard deviation indicating more controlled tracks. With both the outside and staggered scenarios, pilots had no difficulty staying within channel limits while with the inside scenarios some tracks left the channel. This is due to buoys marking the outside of the channel relative to the turn between data lines 7 and 15. Therefore, as a minimum buoys immediately following a turn should be located to the outside of the turn between 3325 feet to 7125 feet following the turn.

The conclusion to be drawn from this data is that one-side buoy configurations never have an advantage. Using an equal density of buoys (one-side, staggered, or gated configuration), gated buoys are better than one-side configurations under good visibility, and staggered buoys are better than one-side buoys when visibility is poor. To ensure safe transits, pilots must know channel boundaries to determine ship position relative to them. Therefore, gated or staggered buoys are the only viable straight channel markings.

# STAGGERED VERSUS INSIDE BUOYS IN LIMITED VISIBILITY

— INSIDE 3/4 NM VIS. (SCEN 8)  
 - - - STAGGERED, 3/4 NM. (SCEN 9)

(O.A.) - AREAS WHERE PROBABILITY OF  
 DIFFERENCE OCCURRING BY CHANCE IS  
 LESS THAN .100

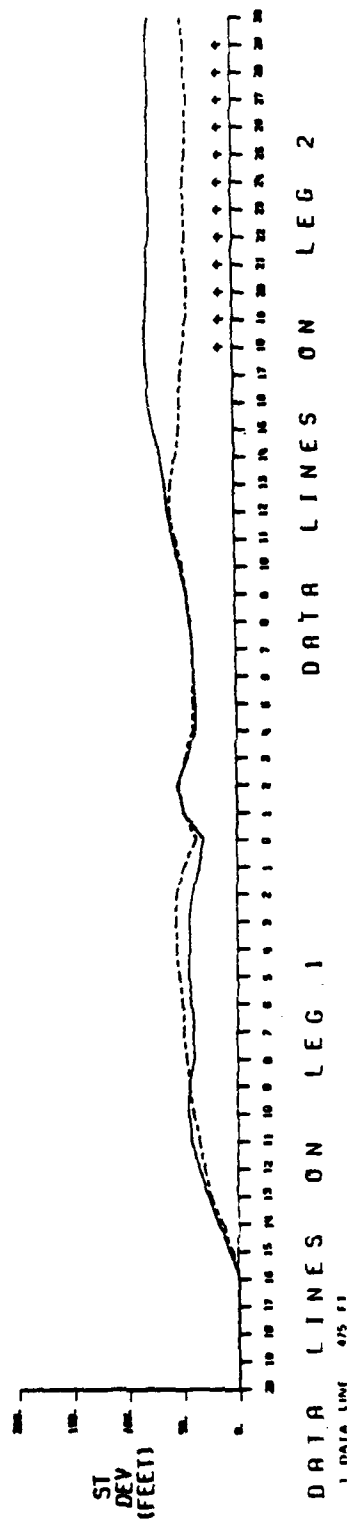
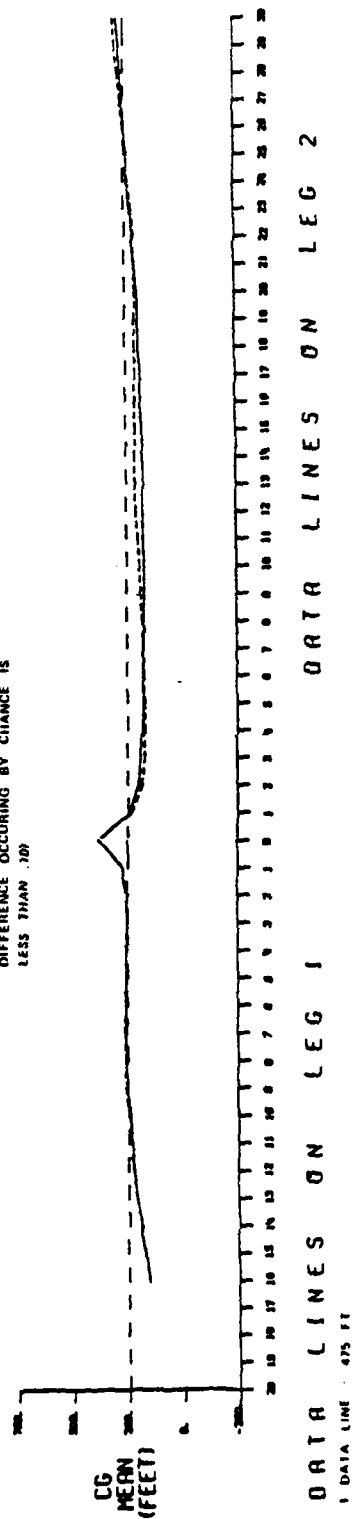


Figure 24. Crosstrack Mean and Standard Deviation of Piloting Performance  
 for Staggered Versus Inside Buoys at Short (3/4 nm) Visibility

## Section 4

### PERFORMANCE AS A FUNCTION OF TURNMARKING

#### 4.1 OVERVIEW

Two-buoy and three-buoy turns were compared to analyze performance differences with different turnmarkings. To minimize learning within the experiment, the two turn scenarios were run immediately after the familiarization scenario. The data indicates that both turn configurations resulted in safe acceptable performance, and all pilots believed both to be workable in an actual channel. Performance differences were (1) higher standard deviation with the three-buoy turn in steadying up in preparation for the turn in leg 1 and (2) a mean closer to the starboard boundary with the two-buoy turn resulting from a tendency to overshoot the turn with gated buoys.

#### 4.2 EFFECT OF TURNMARKING

Scenarios 1 and 6 are identical except in turnmarking. Both scenarios have long-spaced gated buoys marking the straight channel to ensure no design advantage exists in comparing the two turnmarking configurations. Scenario 1 has three buoys marking the turn, and scenario 6 has two buoys in the turn. These scenarios are shown by Figure 25.

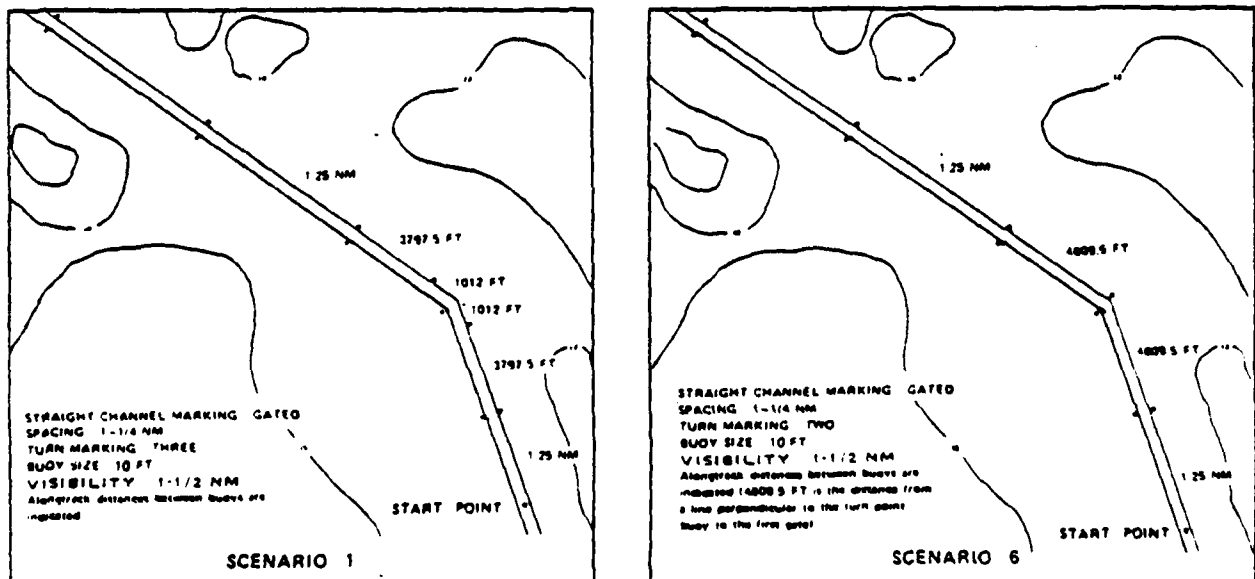


Figure 25. Scenarios 1 and 6

Results from previous CAORF and Channel Width experiments<sup>33,34</sup> showed that the marking in scenario 1 is sufficient to support a smooth turn and pullout. An earlier experiment performed at CAORF<sup>35</sup> for a different project showed the two-buoy turn to be inadequate: there was a tendency to wait to pass through the gate before beginning the turn and to go out of the channel beyond as a result. Since the survey of U.S. ports found the two buoys to be the more frequent turnmarking and because many pilots expressed a preference for it, it is worthwhile to replicate the earlier evaluation. The presimulation hypothesis, therefore, was that performance would be superior in the three-buoy turn, and with two buoys pilots would initiate the turn too late. Actual piloting performance shown by combined track plots in Figure 26 indicates that both turn configurations result in safe, acceptable performance.

When questioned during the postsimulation interview, all pilots believed both turnmarkings were satisfactory and workable in the real world. Three of the pilots preferred the two-buoy turn and five preferred the three-buoy turn. Those who chose the two-buoy turn as better did so because the extremity and exact turning point were marked. This provided information to determine if the ship's stern remained in the channel. The majority, who preferred the three-buoy turn felt it was superior in a large turn (close to 40 degrees) because three reference points were available.

Turn strategies were different for each condition although the black turn buoy was the most heavily relied upon. With the three-buoy turn, most pilots used the angle-off-the-bow of the black turn buoy to initiate the turn, while some pilots used the first turn buoy as a cue to begin the turn. Once in the turn, they determined the rate of swing around the black buoy and then used the third turn buoy to judge the crosstrack movement. Criticism of the two-buoy turn was that (1) the turn may have been initiated too late, (2) it was more difficult to recover from the turn without a buoy marking the outside of the turn, and (3) it was difficult to judge the wind and current effects. Several pilots stated that strategies with the two-buoy turn were to position the ship further to the right to initiate the turn and swing a larger arc to go over to the left and be set to the right. In this way, a less radical turn was made. This can be seen in Figure 27. Again, all pilots believed that under the given conditions both turn configurations were adequate to make a safe turn.

A statistical comparison of the two conditions in both mean crosstrack location and standard deviation is shown by Figure 28. A closeup of the turns is presented in Figure 27. These data indicate that in region 1 there is a significant increase in dispersion of the

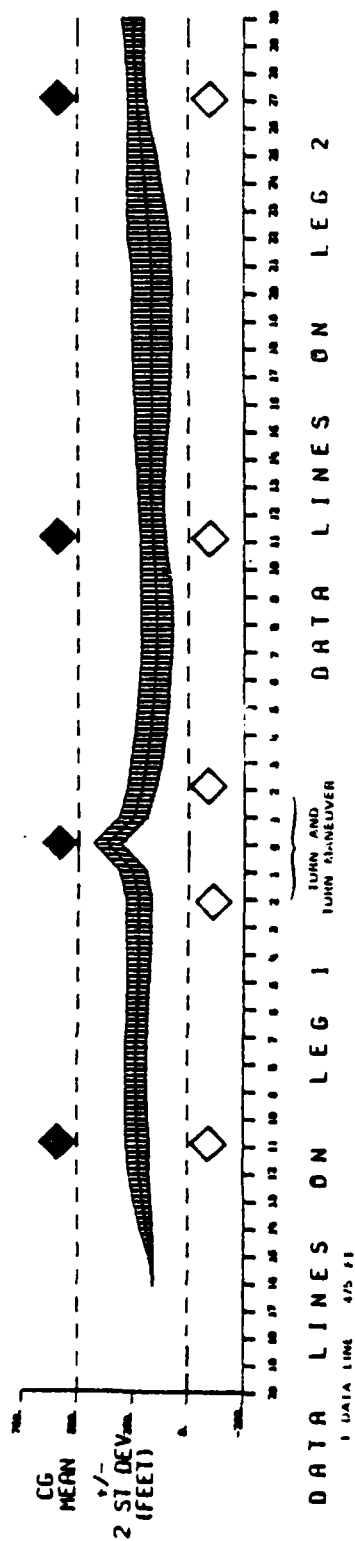
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<sup>33</sup>Ibid.

<sup>34</sup>M.W. Smith and W.R. Bertsche, op. cit., January 1981.

<sup>35</sup>D.A. Atkins and W.R. Bertsche, op. cit.

# SCENARIO 1: LONG-SPACED GATED BUOYS WITH THREE-BUOY TURN



# SCENARIO 6: LONG-SPACED GATED BUOYS WITH TWO-BUOY TURN

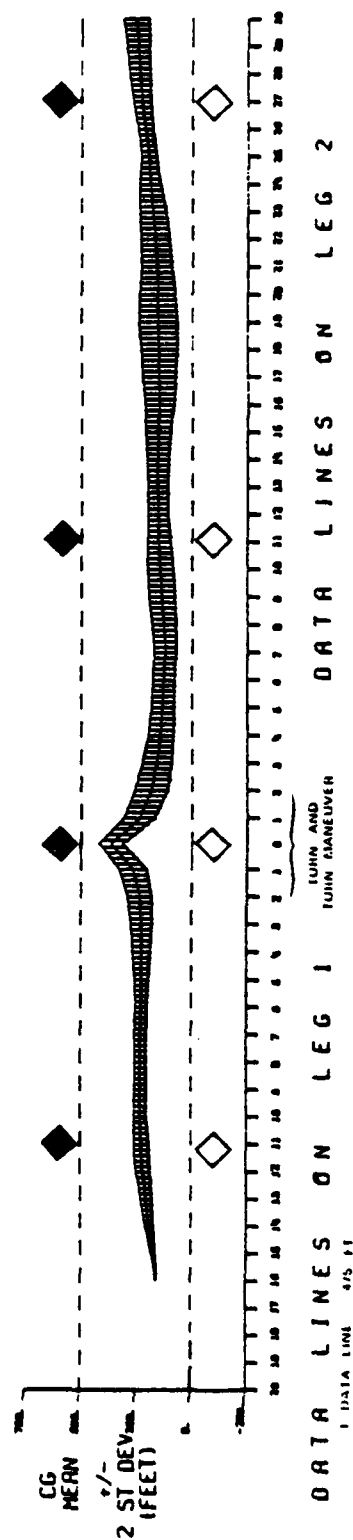


Figure 26. Combined Plots of Piloting Performance With Three-Buoy Versus Two-Buoy Turn at 1 1/2nm Visibility

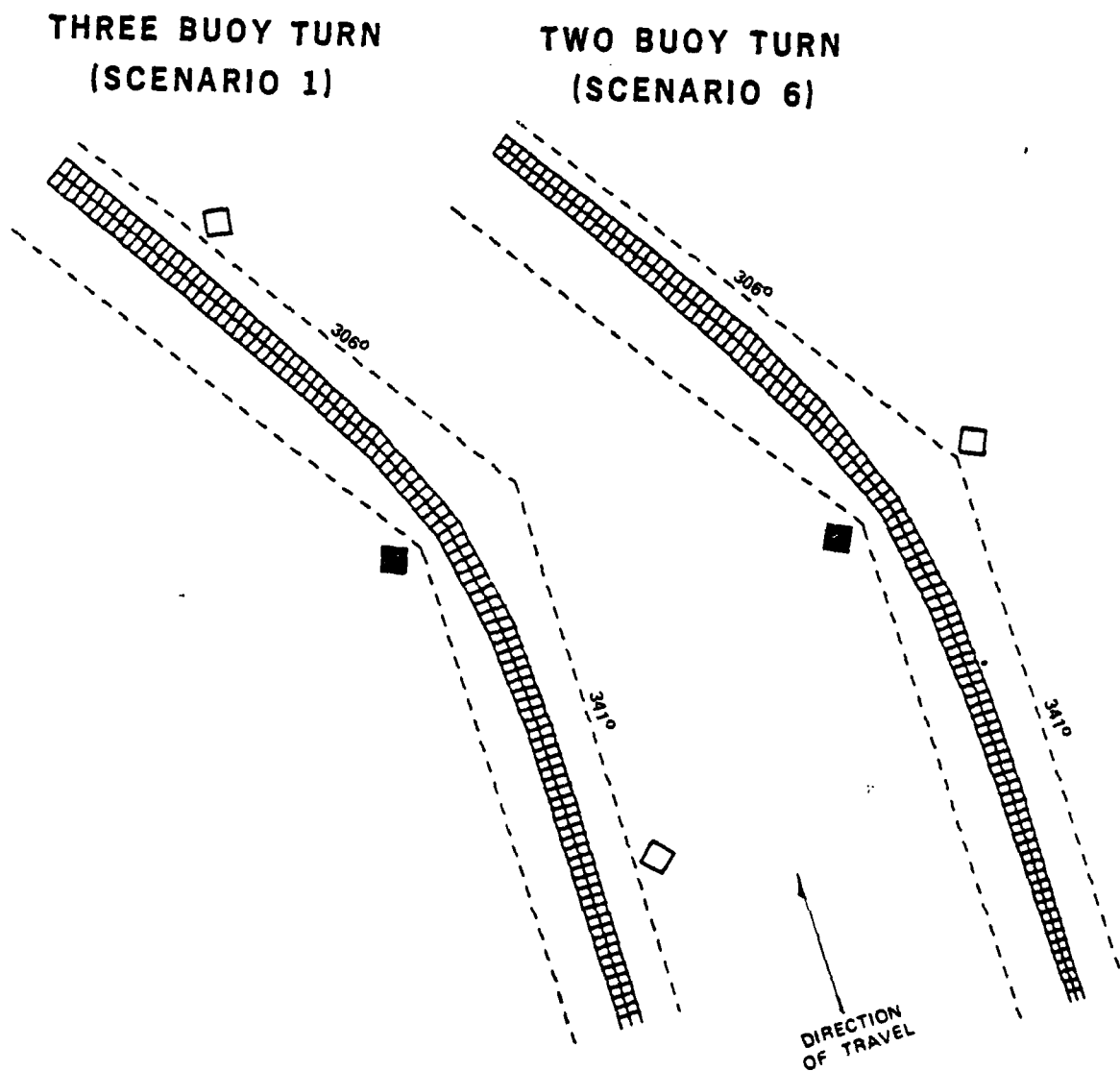


Figure 27. Turn Performance With Two-Buoy and Three-Buoy Turnmarkings

# EFFECT OF TURN MARKINGS

— 3 BUOY MARKING (SCEN 1)  
 - - - 2 BUOY MARKING (SCEN 6)

NO. 9. - AREAS WHERE THE PROBABILITY OF DIFFERENCE  
 OCCURRING BY CHANCE IS LESS THAN .100

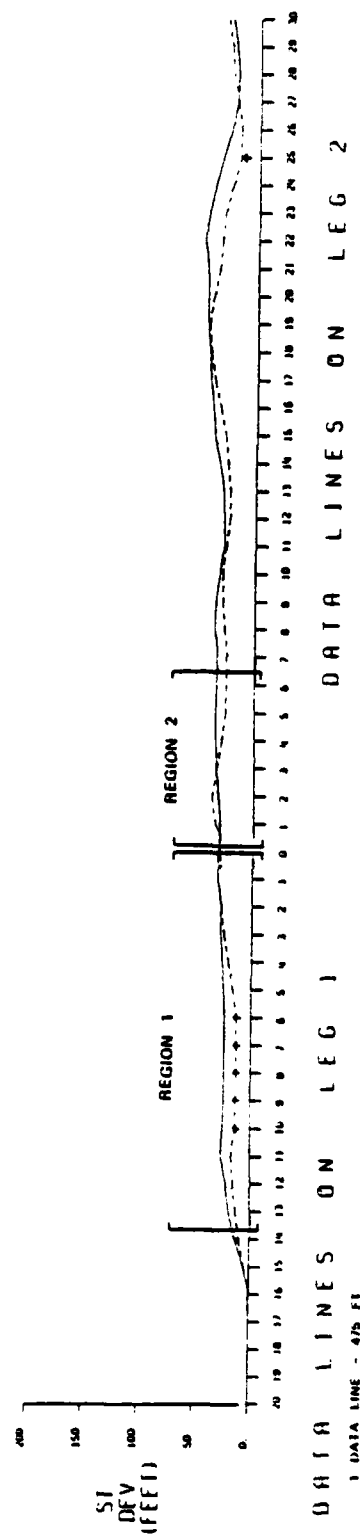
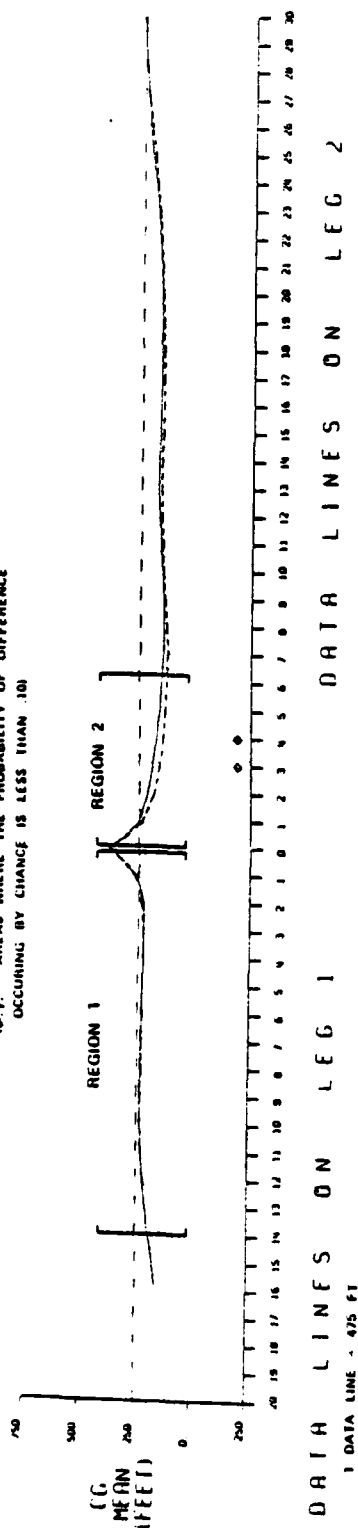


Figure 28. Crosstrack Mean and Standard Deviation of Piloting Performance:  
 Three-Buoy Turn Versus Two-Buoy Turn at 1 1/2 nm Visibility

tracks for the three-buoy turn when compared to the the two-buoy turn. In region 2 the differences between the turnmarkings occur in the means, with the two-buoy mean being significantly closer to the starboard channel boundary. These differences will be discussed in terms of maneuvering for the turn. It must be stressed, however, that both turnmarkings are quite acceptable under the environmental, ship, and turn configuration conditions.

In leg 1, the pilots easily returned to the center of the channel after initially being offset 100 feet to the right at the beginning of the run. The mean and standard deviation of this data is shown below in Table 8. As is seen, the gated scenarios result in a smooth correction for the offset with the mean tracks within 25 feet of the centerline. The dispersion is also small, however, when steadying up in leg 1, the overshoot standard deviation is substantially larger with the three-buoy turn. This is due to the differing strategies used with this turn configuration. Pilots were provided three reference points to determine their crosstrack movement so they were certain of their position when initiating, maneuvering for, and checking the turn; this certainty allowed greater freedom for strategies.

TABLE 8. MANEUVERING ANALYSIS - RETURN TO AND STEADY UP ON CENTERLINE FOR REGION 1

GROUP MEAN		
Performance Measure	3-Buoy Turn (Scenario 1)	2-Buoy Turn (Scenario 6)
Distance to return to centerline (feet before turn)	5043	4861
Overshoot following return to center- line (feet away from turn)	21.7R	24R
Distance to steady up in Leg 1 (feet before turn)	4739	4800
STANDARD DEVIATION		
Performance Measure	3-Buoy Turn (Scenario 1)	2-Buoy Turn (Scenario 6)
Distance to return to centerline (feet before turn)	972	608
Overshoot following return to center- line (feet away from turn)	24.8*	12.6*
Distance to steady up in Leg 1 (feet before turn)	972	608
R = Right of Centerline		
*Probability less than .10 of occurring by chance		

The initial turn rudder application (see Table 9) in both turns was similar with the pilots ordering equal magnitude of initial rudder. The turn, however, was initiated one data line (475 feet) earlier with the three-buoy turn, probably due to cueing from the first turn buoy. Also, the mean frequency of turn rudder actuations was slightly larger with the three-buoy turn. Again, more rudder orders have been associated with greater pilot control resulting from more buoys available as reference points.

TABLE 9. MANEUVERING ANALYSIS - INITIAL  
TURN RUDDER APPLICATION

GROUP MEAN		
Performance Measure	3-Buoy Turn (Scenario 1)	2-Buoy Turn (Scenario 6)
Distance before turn at initial rudder (feet)	1425	1033
Magnitude of initial rudder (degrees)	10	10
Frequency of turn rudder actuations	6	2
STANDARD DEVIATION		
Performance Measure	3-Buoy Turn (Scenario 1)	2-Buoy Turn (Scenario 6)
Distance before turn at initial rudder (feet)	304	365
Magnitude of initial rudder (degrees)	5	5
Frequency of turn rudder actuations	5	2

Pilot performance while actually in the turn is not significantly different. As stated in the preliminary observations for this report <sup>36</sup>, this was due to a consistently heavier reliance on the inside apex turn buoy. Regardless of turn configuration, most pilots watched the angle-off-the-bow of the apex buoy and the ship's movement in relation to it.

The configuration performance differences occur most significantly when recovering from the turn. This occurs in region 2, and data for this is shown by Table 10. Here, although both means were safe, the

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<sup>36</sup>Eclectech Associates, op. cit.

resultant mean for the two-buoy turn was significantly further toward the starboard channel boundary (32 feet). In part this was due to strategy difference. Because the pilots suspected they could have difficulty judging the channel boundaries and the ship's set to the right, several pilots stated they would position the ship further to the left to initiate the turn then let the wind and current push the ship to the right at the entrance at leg 2 and steady the ship on the centerline with the first pair of gates. With the three-buoy turn, the third turn buoy allowed quicker turn recovery since it was positioned to judge the set easily. The lack of this buoy resulted in less certainty of ships set immediately after the turn and thus effected the set of the mean to the right.

TABLE 10. MANEUVERING ANALYSIS -  
CROSSTRACK DATA FOR REGION 2

MAXIMUM MEAN CROSSTRACK POSITION		
	3-Buoy Turn (Scenario 1)	2-Buoy Turn (Scenario 6)
Region 1 (feet)	24.1R	23.4R
Region 2 (feet)	77.4R	108.6R*
MAXIMUM CROSSTRACK STANDARD DEVIATION		
	3-Buoy Turn (Scenario 1)	2-Buoy Turn (Scenario 6)
Region 1 (feet)	24.0*	13
Region 2 (feet)	34.8	34.4
R = Right of Centerline		
*Probability less than .10 of occurring by chance		

It has been shown both by pilot opinion and pilot performance that the two-buoy and three-buoy turns are acceptable in a large turn under the given conditions. The three-buoy turn is preferred by 62 percent of the pilots since it provides more cues to judge the ship position. The two-buoy turn is preferred by 38 percent of the pilots because the extremities of the turn are marked. The three-buoy turn results in a significant (but not essential) improvement of the mean track.

This data can be compared to turnmarking data collected during the CAORF experiment. In this experiment turnmarking was found to have a significant impact on navigation safety with the three-buoy turn resulting in superior performance when compared to a one-buoy turn. It should be noted, however, that while there were substantial differences between one- and three-buoy turns, these were judged against a large variety of conditions including: (1) straight channel markings (gated

or staggered), (2) buoy spacing ( $5/8$  nm or  $1-1/4$  nm), (3) lighting (day or night), (4) detection range ( $3/4$  nm or  $1-1/2$  nm), (5) angle of turn, and (6) turn radius (cutoff versus noncutoff). In the one-side experiment conditions were held constant except for turnmarking.

To compare findings of the one-side experiment to those found during the CAORF experiment, a scenario which is identical to the one-side scenarios 1 and 6 in all but turnmarking should be selected. However, no such scenario exists due to the nature of the fractional factorial design which attempted to evaluate a cross-section of 128 conditions. Therefore, similar scenarios must be selected to evaluate one-, two- and three-buoy turnmarkings. The scenarios must include a one-buoy turn run at daytime and must mark a 35-degree noncutoff turn. Only scenarios 19 and 21 fall into this category; these are shown by Figure 29. Scenario 19 has the required buoy spacing but not the buoy configuration, and scenario 21 has the appropriate gated buoy configuration but spacing is too small for a perfect comparison. Several conclusions, however, can be drawn for this data.

One-buoy turns are inadequate if the straight legs are marked inadequately, however, it results in satisfactory turn performance if the straight leg is well-marked. The two-buoy turn performance (Scenario 6) appears to be analogous with the one-buoy turn with short-spaced gates following (CAORF Scenario 21) because the gate can be seen when recovering from the turn. Therefore, one- and two-buoy turns result in acceptable performance during the day only if the straight channel is marked by long-spaced gated buoys.

The three-buoy turn consistently results in satisfactory turn performance regardless of straight channel marking; it provides enough information to complete the turn without relying on the following straight channel marking. Three-buoy turns add protection against poor conditions such as limited visibility or night when it is more difficult to visualize the entire turn. Also, since the ship variable experiment showed larger ships were difficult to maneuver through a sparsely marked turn, the three-buoy turn would better prepare a pilot to take the ship through the turn.

Further testing of this configuration difference under night conditions is suggested to identify if the overshoot observed with the two-buoy configuration is exaggerated at night. A large dependence of turnmarking and night conditions has been identified in the previous CAORF experiment.<sup>37</sup> Also, different sizes of ships could be run through the turn since it has been shown in the Ship Variables Experiment<sup>38</sup> that performance with larger ships is generally poorer than smaller ships and is more dependent on high buoy densities.

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<sup>37</sup>M. W. Smith and W. R. Bertsche, op. cit., August 1980.

<sup>38</sup>W. R. Bertsche, D. A. Atkins, and M. W. Smith, op cit.

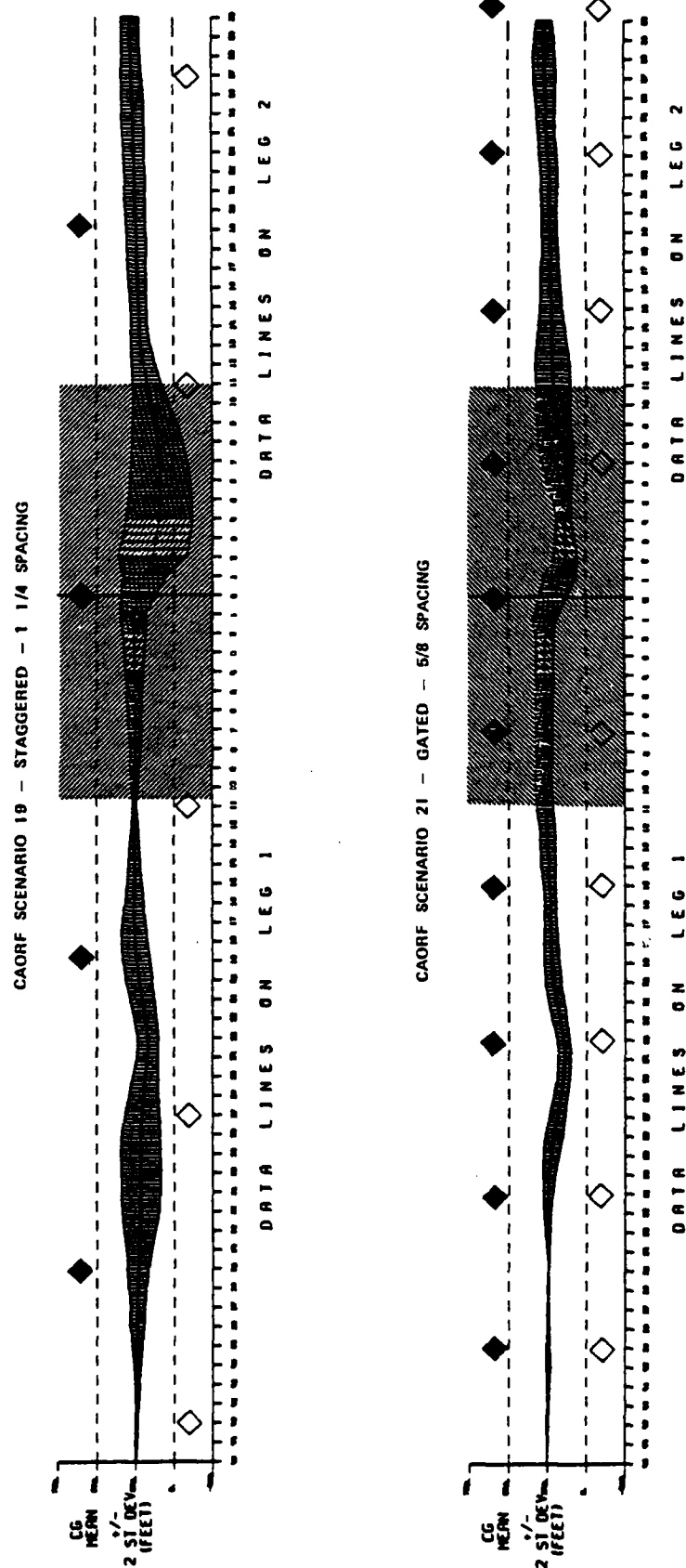


Figure 29. Combined Plots of Piloting Performance with CAORF One-Buoy Turns:  
Staggered 1-1/4 Spacing Versus Gated 5/8 Spacing

## Section 5

### PERFORMANCE AS A FUNCTION OF BUOY SIZE

#### 5.1 OVERVIEW

A new more detailed buoy image was developed to present pilots with a more realistic simulation and to determine if buoy size and detail affected performance. Ten-foot (7'x17') and 17-foot (9'x32') buoys were used to mark otherwise identical scenarios to assess performance differences. The analysis showed no meaningful performance differences. Implication for real world channel design are that buoy size should not affect performance within the range that pilots can see the buoys equally. If a taller buoy can be seen earlier than a shorter buoy, then performance may be improved by taller buoys. As long as a buoy can be seen, buoy size has no impact on performance.

#### 5.2 EFFECT OF BUOY SIZE

In this experiment, the new more detailed 10-foot buoys were used in all scenarios but one. Scenarios 2 and 7 are identical except that scenario 7 has the old 17-foot solid buoys which had been used for all prior experiments. The scenarios are shown below in Figure 30.

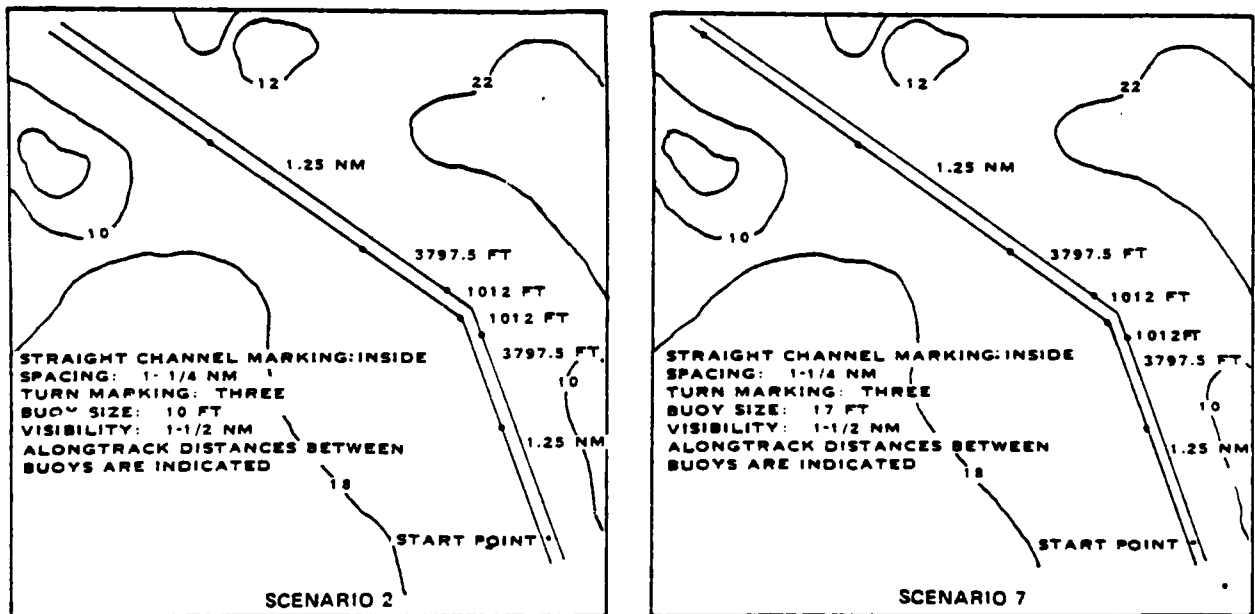


Figure 30. Scenarios 2 and 7

In the presimulation report <sup>39</sup>, it was hypothesized that buoy size is irrelevant when buoys are used for perspective or aiming information, but it is relevant when they are used for distance-off information, close or abeam. It was further speculated that with one-side markings, the pilot is likely to depend more on distance-off cues because the

<sup>39</sup>M.W. Smith, op cit.

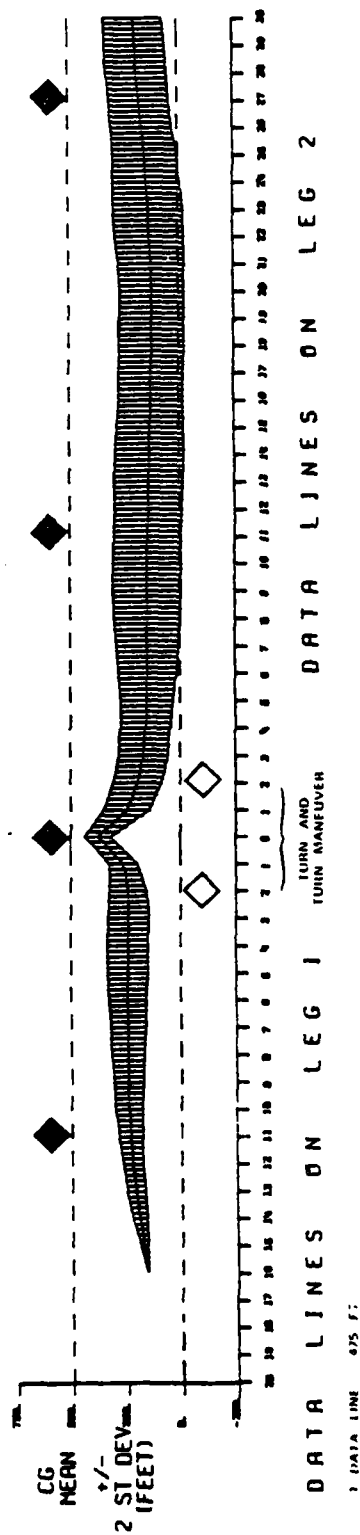
marking is not as useful as gates for perspective or aiming information. Also, in long-spaced conditions, the pilot is likely to depend on distance-off information since there are not always buoys straight ahead for aiming information. Scenario 2 fits this criteria, so it was chosen to be rerun as scenario 7 to determine if a difference due to buoy size exists.

Figures 31 and 32 show there are no meaningful piloting performance differences for 10-foot versus 17-foot buoys. Figure 31 shows the combined plots for the data and Figure 32 details the crosstrack mean and standard deviation differences of the data.

The pilots stated that buoy size had no effect on their piloting, and they did not use the buoys differently. Generally, they preferred the new "open" 10-foot buoy that had a cylindrical base, support struts, and a radar reflector as opposed to the 17-foot solid buoy which had a cylindrical base and cylindrical solid superstructure. In this simulation, the buoys appeared on the screen at the same time as a function of visibility regardless of size. They were hazy when they first appeared and became clearer as the ship moved closer. The differences between buoy details were seen when the buoys were close by an increase in height (17-foot buoy) or an increase in detail (10-foot buoys). Some of the pilots, however, believed large buoys were more desirable since they were more visible in the distance.

These scenarios again illustrate the inadequate pilot performance when using long-spaced, one-side buoys. In the second leg, the mean tracks are continually to the right of the channel even as wind and current decrease. In both scenarios, the track envelope lies out of the channel and the standard deviation is wide further demonstrating that this one-side marking is unacceptable.

# SCENARIO 2: INSIDE CHANNEL MARKINGS AT 1-1/4 NM APART WITH 10 FOOT BUOYS



# SCENARIO 7: INSIDE CHANNEL MARKINGS AT 1-1/4 NM APART WITH 17 FOOT BUOYS

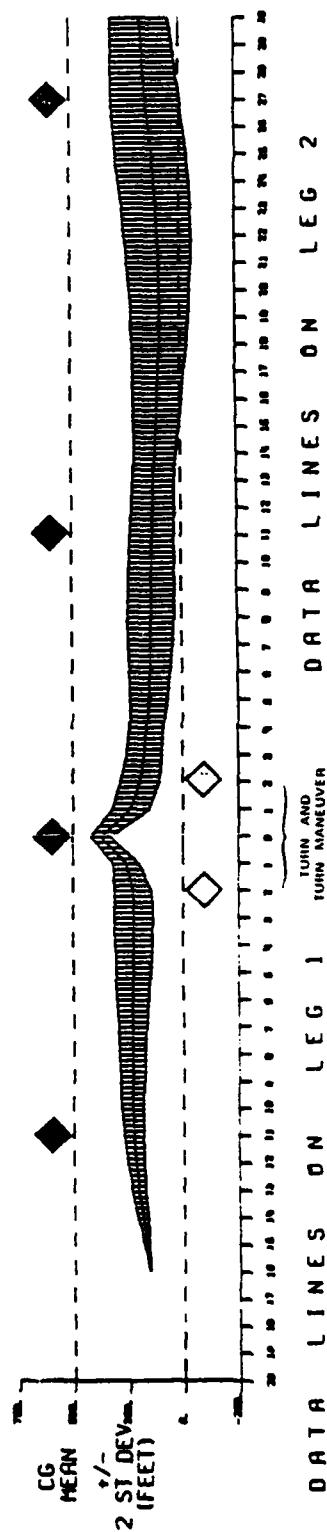


Figure 31. Combined Plots of Piloting Performance 10-Foot Versus 17-Foot Buoys for One-Side Channel Markings in 1-1/2 nm Visibility

EFFECT OF BUOY SIZE

— 10 FT BUOYS (SCEN 2)  
 --- 17 FT BUOYS (SCEN 7)

IND STATISTICAL DIFFERENCE INDICATED  
 AT 10 LEVEL OF SIGNIFICANCE

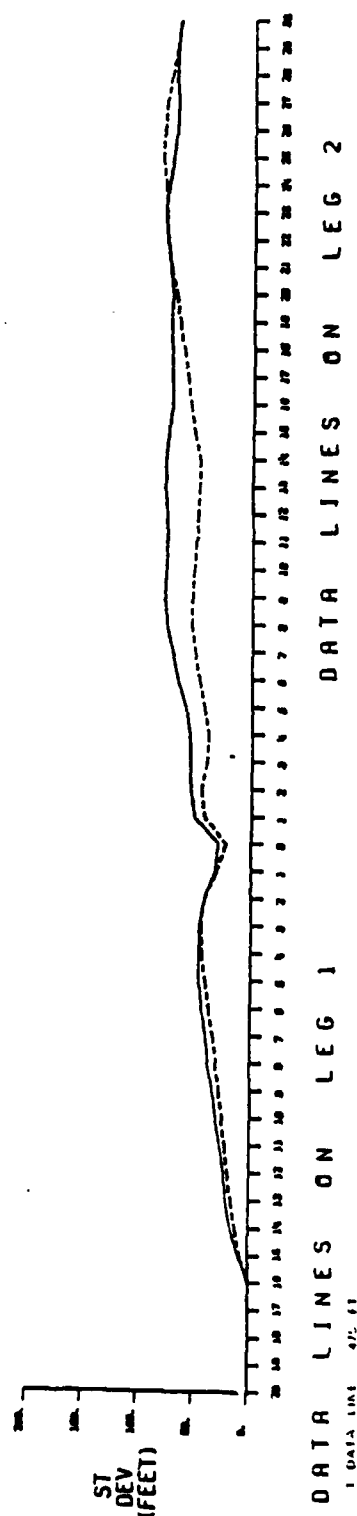
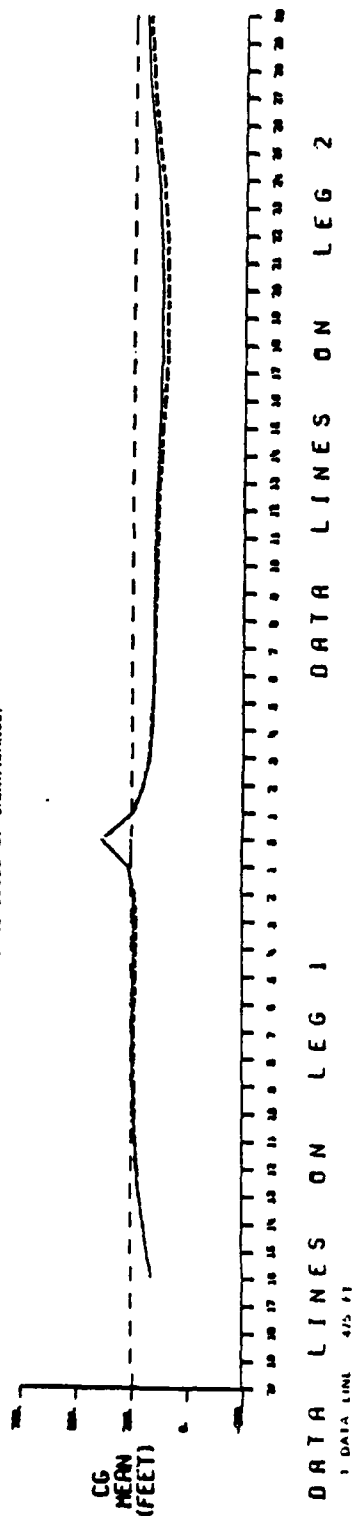
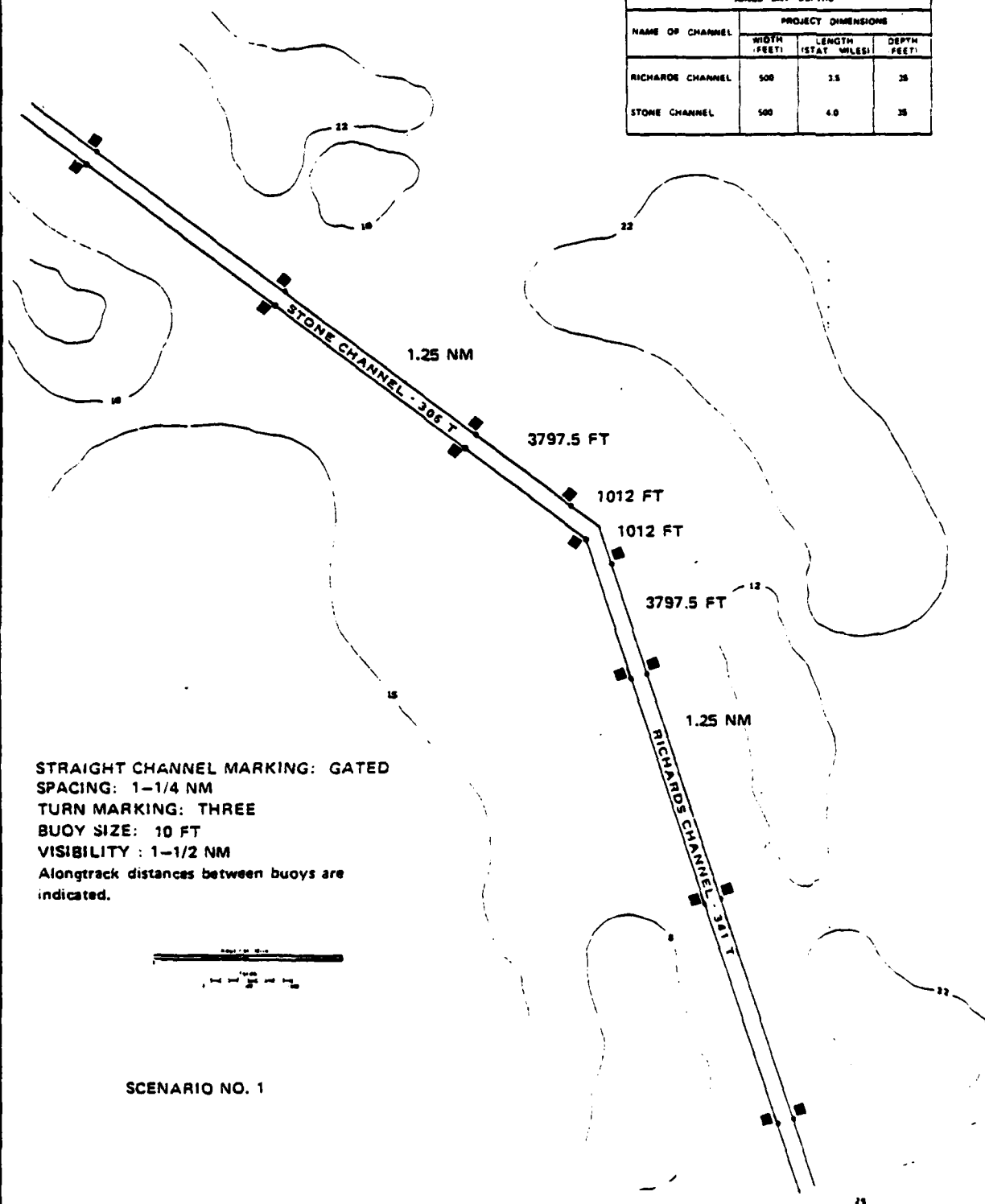


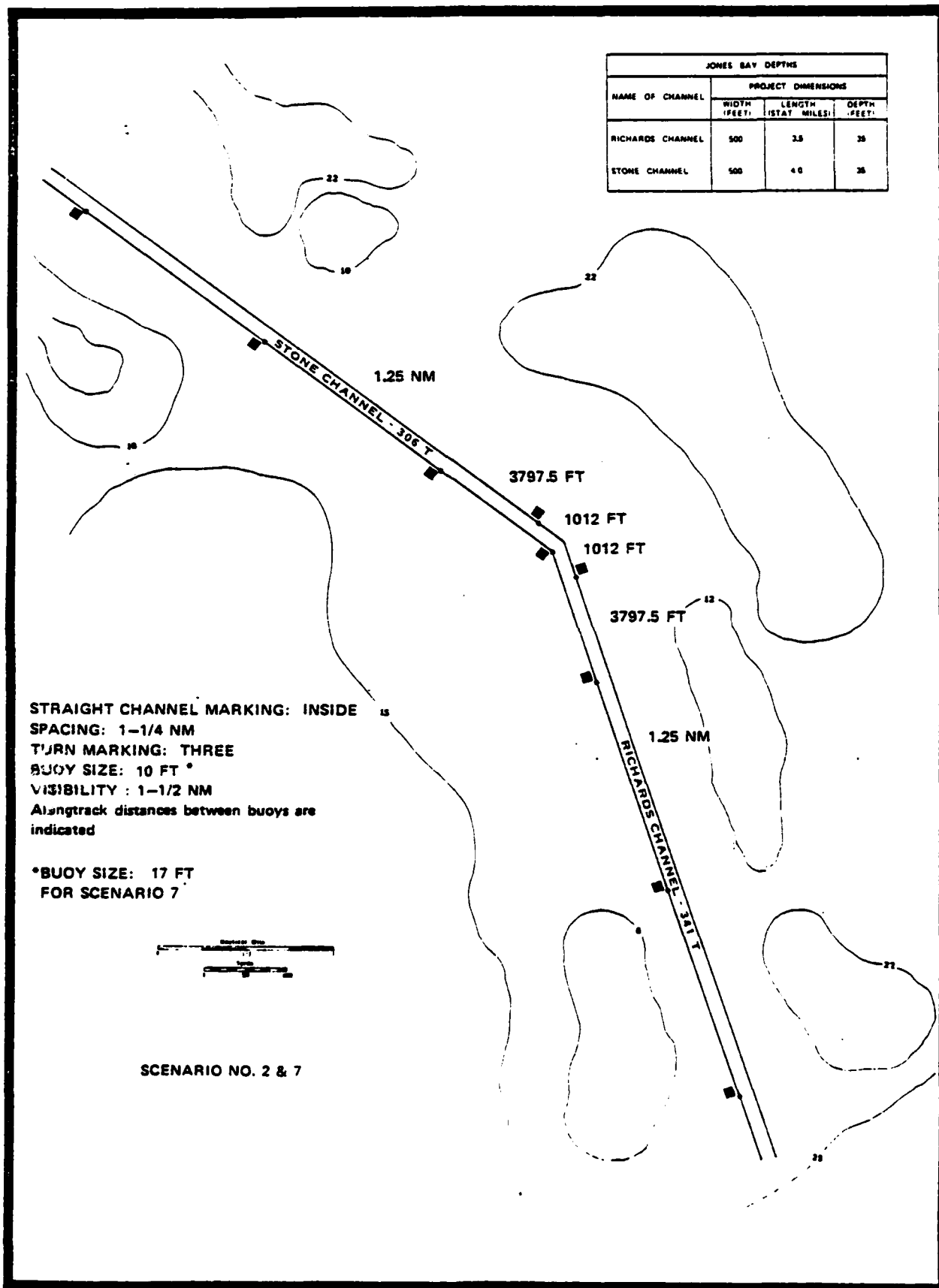
Figure 32. Crosstrack Mean and Standard Deviation of  
 Piloting Performance 10-Foot Versus 17-Foot Buoys

## APPENDIX A

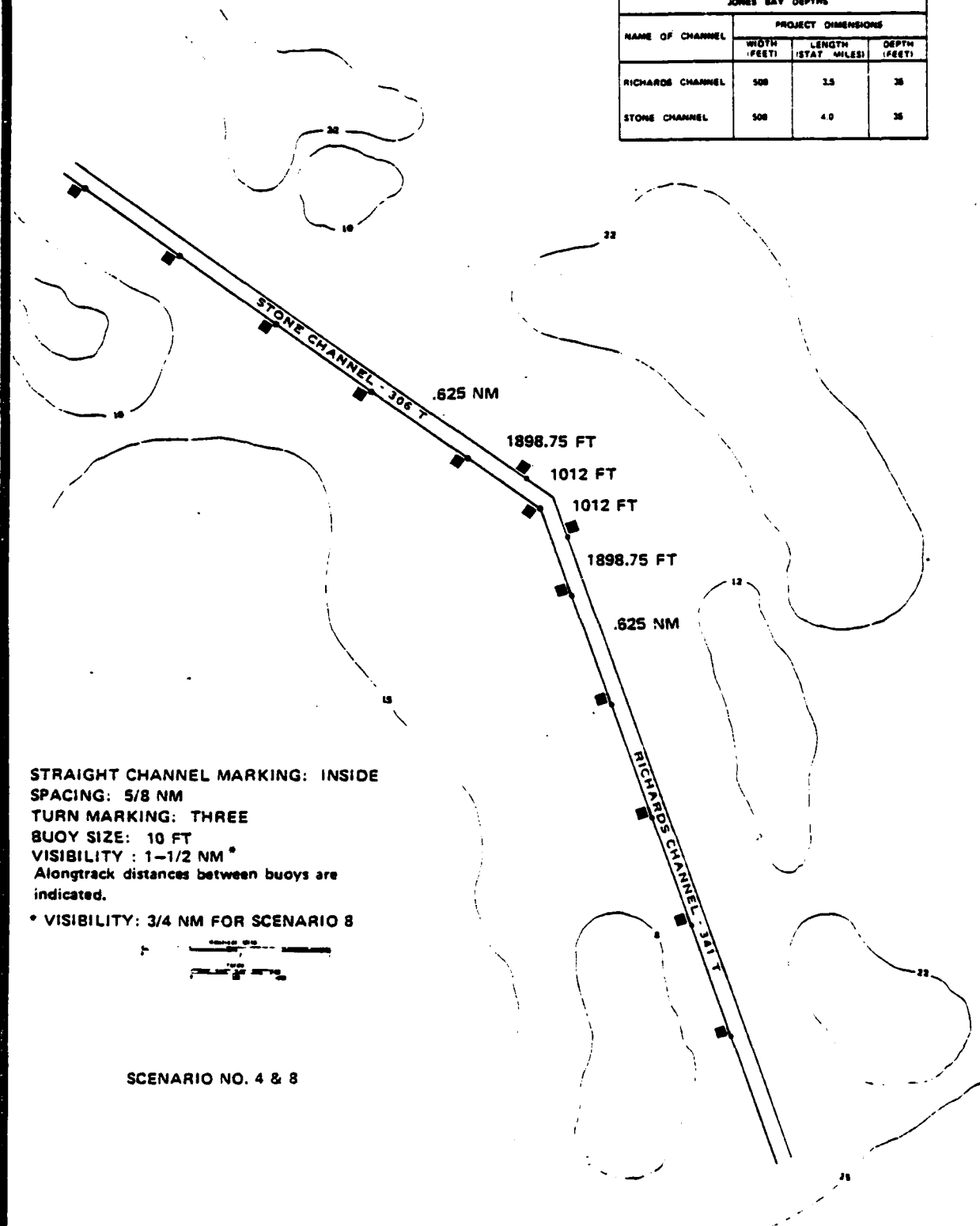
### SCENARIOS

JONES BAY DEPTHS			
NAME OF CHANNEL	PROJECT DIMENSIONS		
	WIDTH (FEET)	LENGTH (STAT. MILES)	DEPTH (FEET)
RICHARDS CHANNEL	500	3.5	25
STONE CHANNEL	500	4.0	25





JONES BAY DEPTHS			
NAME OF CHANNEL	PROJECT DIMENSIONS		
	WIDTH (FEET)	LENGTH (STAT. MILES)	DEPTH (FEET)
RICHARDS CHANNEL	500	2.5	25
STONE CHANNEL	500	4.0	25

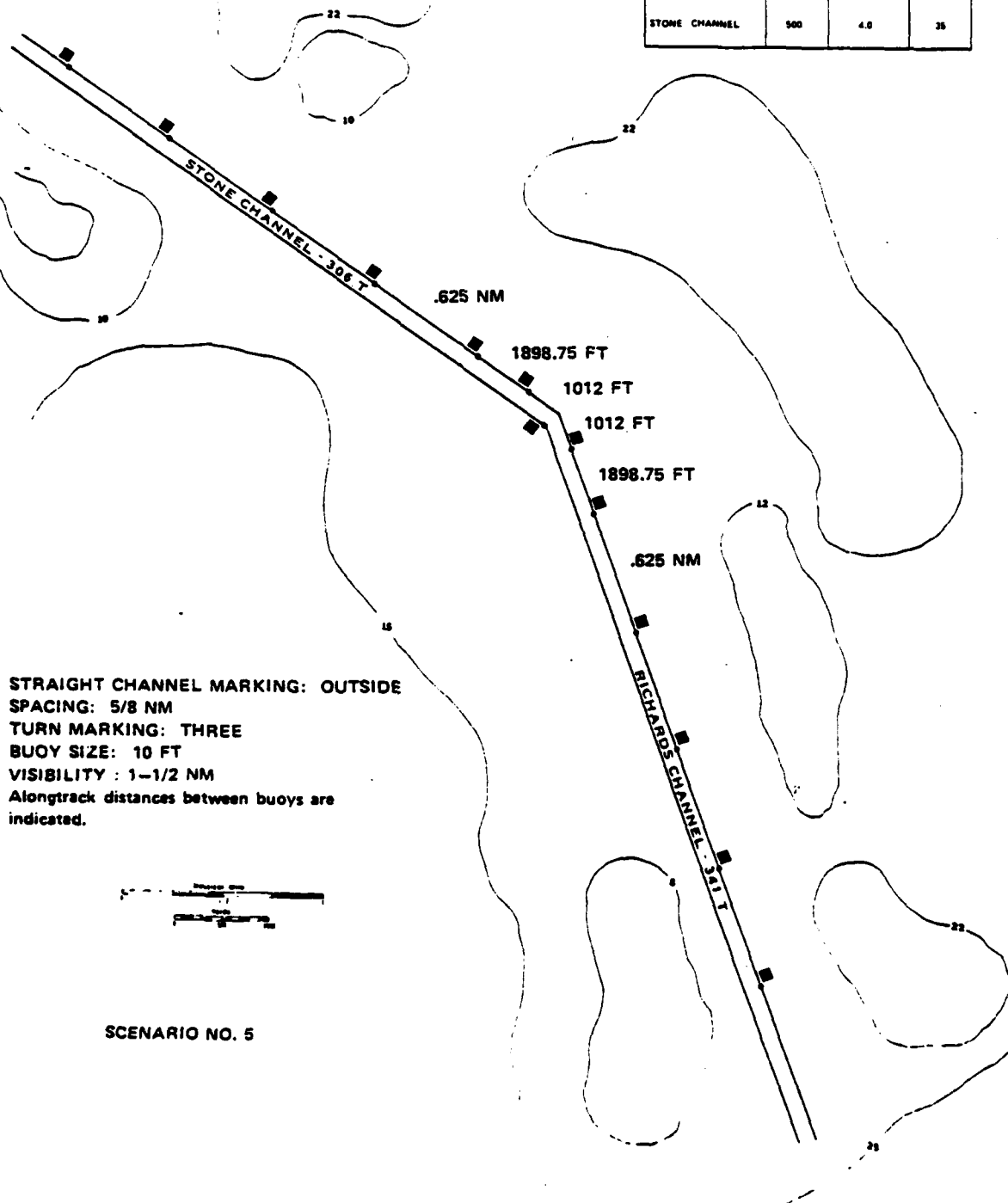


STRAIGHT CHANNEL MARKING: INSIDE  
 SPACING: 5/8 NM  
 TURN MARKING: THREE  
 BUOY SIZE: 10 FT  
 VISIBILITY : 1-1/2 NM \*  
 Alongtrack distances between buoys are  
 indicated.

\* VISIBILITY: 3/4 NM FOR SCENARIO 8

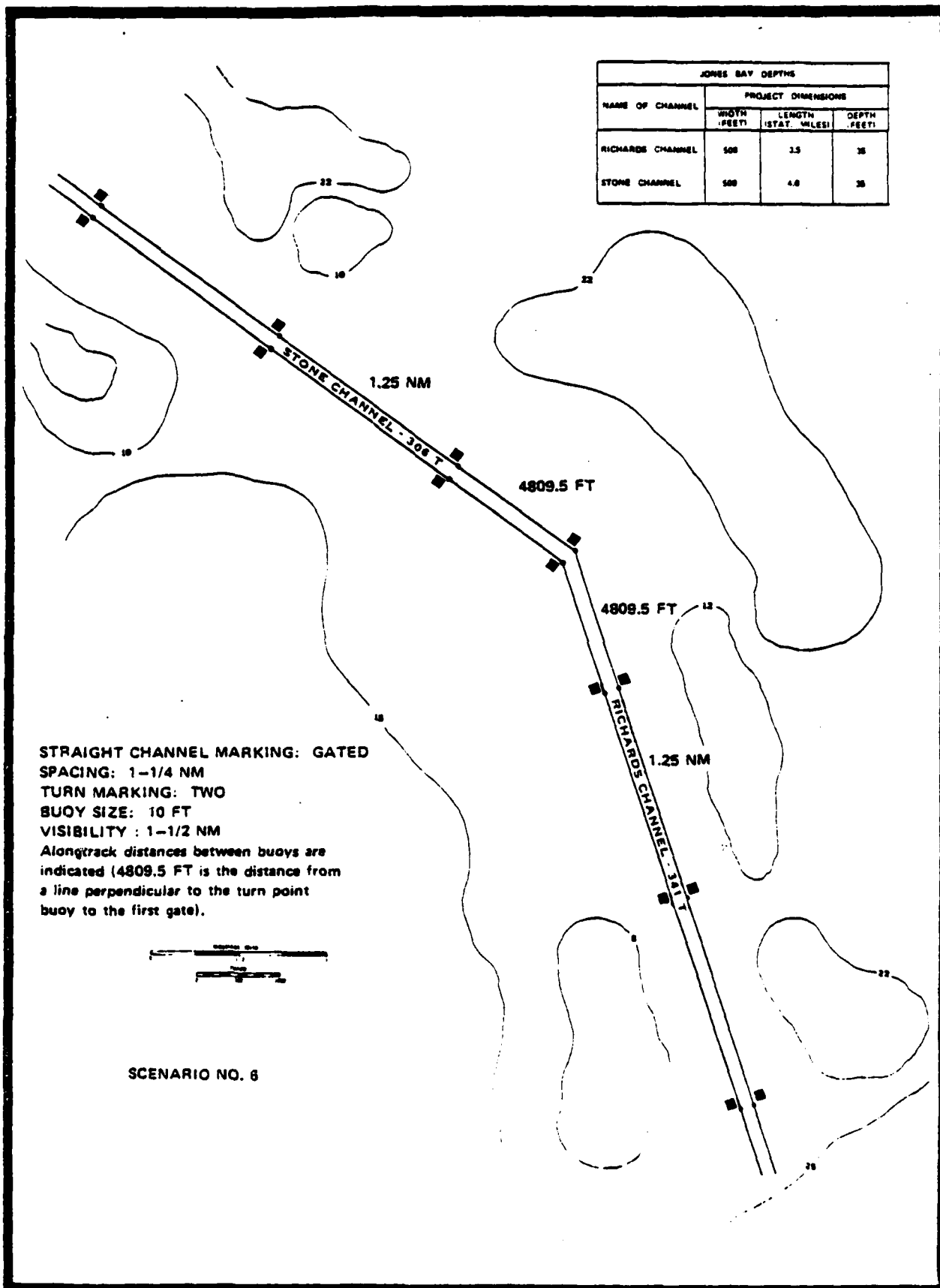
SCENARIO NO. 4 & 8

JONES BAY DEPTHS			
NAME OF CHL.	PROJECT DIMENSIONS		
	WIDTH (FEET)	LENGTH (STAT. MILES)	DEPTH (FEET)
RICHARDS CHANNEL	500	3.5	35
STONE CHANNEL	500	4.0	35

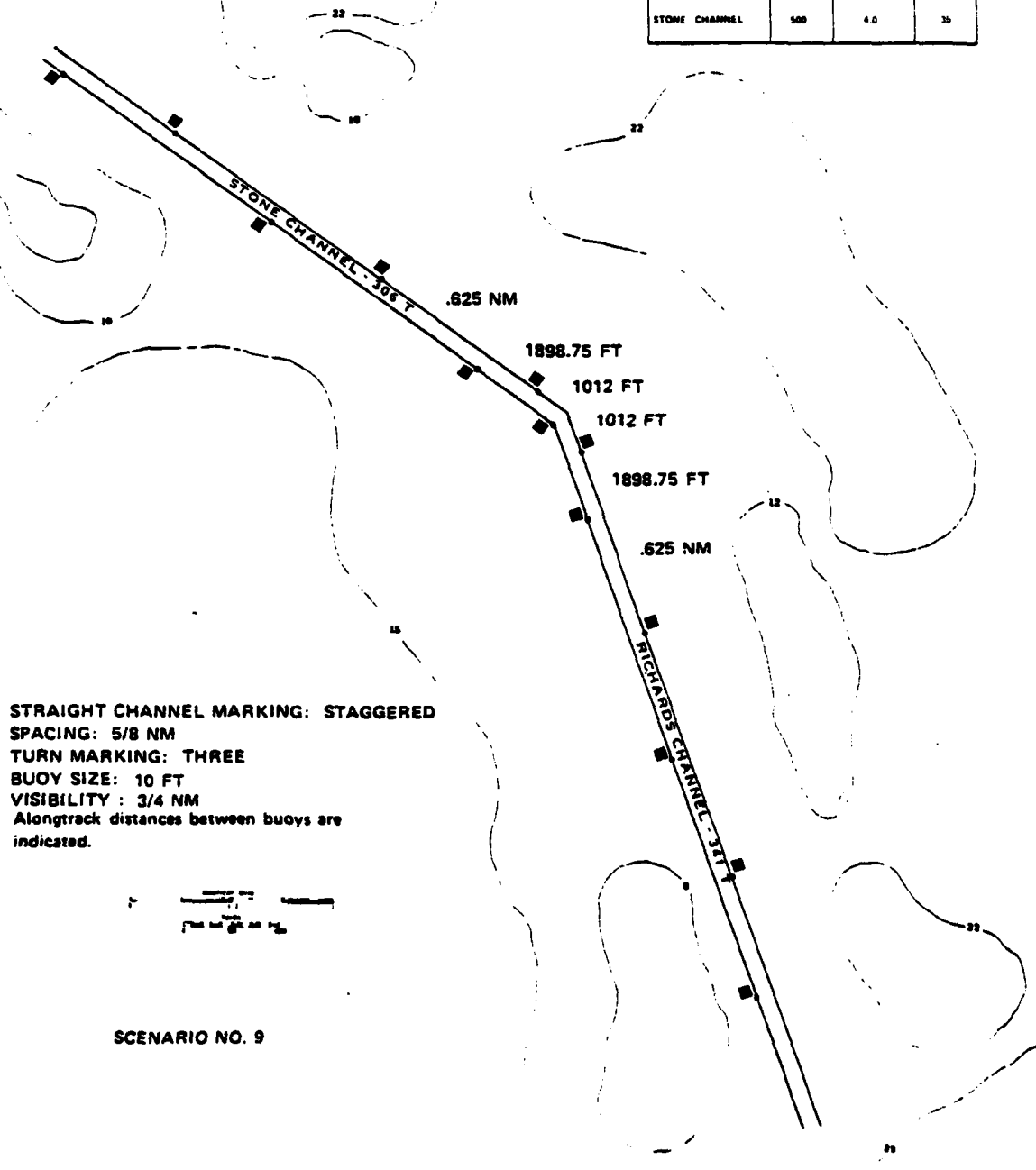


STRAIGHT CHANNEL MARKING: OUTSIDE  
 SPACING: 5/8 NM  
 TURN MARKING: THREE  
 BUOY SIZE: 10 FT  
 VISIBILITY : 1-1/2 NM  
 Alongtrack distances between buoys are  
 indicated.

SCENARIO NO. 5



NAME OF CHANNEL	KIA-1 BAY DEPTHS		
	PROJECT DIMENSIONS		
	WIDTH (FEET)	LENGTH (STAT MILES)	DEPTH (FEET)
RICHARDS CHANNEL	500	2.5	25
STONE CHANNEL	500	4.0	35



## Appendix B

### ONE-SIDE EXPERIMENT: INSTRUCTIONS TO THE PILOT

#### B.1 INTRODUCTION

It has been suggested that the critical factor in visual aids to navigation is the alongtrack distance between aids abeam. If this is the case, buoys along one side will provide the needed buoys with one-half the number needed by gates. The principal purpose of this experiment is to compare piloting using buoys placed along one side of the channel with piloting using gated and staggered buoy configurations.

Other conditions in this experiment include the single row of buoys to the inside or outside relative to the turn, the single row of buoys spaced at shorter or longer intervals, turns marked with two or three buoys, buoys of 17 or 10 feet in height, and visibility at 1-1/2 or 3/4 nm.

There will be a total of eight scenarios. The first will familiarize you with the wind and current, and the others will be experimental scenarios, differing in the conditions named above. They will be approximately 40 minutes long. At the end of the day, there will be a questionnaire for you to express your opinion on the conditions of the experiment.

#### B.2 CONDITIONS COMMON TO ALL SCENARIOS

a. The channel and environmental conditions: The general layout of the channel and current conditions are illustrated in Figure B-1. The scenarios contain a 500-foot wide channel, marked as indicated on each chart. The whole scenario has shallow water effects. There are no bank effects in the channel. The channel has a 35-degree turn to the left with no cutoff.

The current is 1-1/4 knots at 341 degrees True at the beginning of the run. It moves up the channel in its first leg, decreasing to 3/4 knot at the turn. There it is broad on the port quarter at the pullout. In the second leg, the current gradually turns to follow the channel again. It decreases in speed until it is 0 knots when the scenario ends.

There is a gusting wind averaging 30 knots throughout the scenario. It maintains an average direction of 161 degrees True throughout the run.

b. The ship: The ship is a 30,000 dwt tanker with a split-house configuration and a viewing point located 75 feet forward from the ship's center of gravity. It has a 595 LOA, an 84-foot beam, a 45-foot height of eye, and a 34-foot draft. It will handle as if it were in shallow water.

c. Speed: Speed at initialization will be 6 knots through the water. Please maintain the set speed. You may change speed to

negotiate the turn if you think it necessary. Please return to the initial speed as soon as possible in the second leg.

d. Initialization conditions: This ship will be initialized 1.3 nm below the turn and 100 feet to the right of the centerline with a heading equal to the channel course of 341 degrees True.

e. Maneuvering instructions: When you take control, please move the ship to the centerline as quickly as you think prudent. Stay on the centerline trying to keep as strict a definition of "centerline" as is practical. You may leave the centerline when you decide it is necessary for the approach to the turn. Use your own strategy to negotiate the turn. In the second leg, return to the centerline as soon as possible and maintain it until the end of the run.

f. Bridge conditions: There will be:

- a helmsman on the bridge to receive your orders
- a gyrocompass
- an engine order telegraph
- charts and a current diagram

g. Visual conditions: All experimental scenarios will be run under daytime conditions with visibility at 3/4 or 1-1/2 nm. You will see unlit buoys in these daytime scenarios. It is important that you stay at the center of the bridge. It is only there that the buoys appear in the proper locations and perspective for the conditions.

### B.3 PERCEPTUAL MEASURES

a. There are arrangements for an extra measure of just how well the conditions allow you to judge the ship's position in the channel. There is a panel on the bridge with buttons for you to press to indicate the ship's position relative to the centerline. (See Figure B-2.) The buttons will light up about once a minute. Please press one to indicate whether the ship is to the right, on the centerline, or the left of the centerline. When you press a button, hold it down until the light goes off. If you do not press it, it will go off in 30 seconds.

b. Please make these judgements as precise as possible. Define the position of the ship as the position of its center of gravity and define the centerline of the channel as narrowly as possible.

Press the "CL" button only when you consider the center of gravity of the ship to be on the exact centerline. Press the "L" or "R" button when you consider it to be to the left or right of the centerline. It is not necessary to order a heading change because you indicate the ship is not on the exact centerline if you do not think it is practical to try to bring it closer to the centerline than it is. When the ship's center of gravity is not at the centerline because of maneuvering requirements, indicate its relationship to the centerline from wherever it is.

c. Please respond to the lights as frequently as possible, guessing if you think you have a chance of being correct. If you have no idea at all where the ship is and do not want to guess, do not press anything. The lights will go off in 30 seconds.

d. Please judge the ship's position as accurately as you can each time. Make each judgement independently of the one before. It is not necessary to be consistent from one response to the next.

Please feel free to ask questions or make comments at any time.

#### B.4 ONE-SIDE EXPERIMENT: POSTSIMULATION QUESTIONNAIRE

##### B.4.1 Conditions common to all scenarios.

1.1 Visual conditions: Did the buoys look right to you: their size, location, and movement? Did they have any effect on piloting that you would like to describe?

1.2 Current and wind effects: Were the current and wind effects realistic and as described in the instructions? How did they affect your piloting?

Was the familiarization scenario at the beginning of the day adequate and appropriate to familiarize you with the current and wind? Would you have wanted more or different familiarization opportunities?

1.3 Instructions to keep the ship on the centerline: Were the instructions to keep the ship on the centerline, except when necessary to leave it to maneuver realistic? What would you have preferred to do? Would the size of the ship or any other factor have influenced your preference?

1.4 Instructions to stand at the center of the bridge: Were the instructions to stand at the center of the bridge realistic? How did that affect your piloting?

1.5 Lack of radar: Was the lack of radar realistic for the conditions? Would you have used radar? How frequently would you use it and for what purpose?

##### B.4.2 Conditions that differed among scenarios.

2.1 What was the difference between piloting with gates or one-side markings for long spacing conditions? Did you use the configurations differently? Was there a difference in results? (Scenarios 1 versus 2)

2.2 Was piloting with buoys on one side improved by shortening the spacing? Did you use the conditions differently? Was there a difference in results? (Scenarios 2 versus 4)

- 2.3 Given the same density of buoys in 1-1/2 nm visibility, is it preferable to have the long-spaced gated or short-spaced one side marking? (Scenarios 1 versus 4 and 5)
- 2.4 Given the same density of buoys in limited (3/4 nm) visibility, which buoy configurations (long-spaced staggered versus short-spaced one side) did you prefer? What was the difference in your strategy? Would your preference change in improved visibility? (Scenarios 8 versus 9)
- 2.5 What effect did the turnmarking have on piloting? Did you use the configurations differently? Was there a difference in the results? (Scenarios 5 versus 6)
- 2.6 What effect did buoy size have on piloting? Did you use the different-sized buoys differently? (Scenarios 2 versus 7)
- 2.7 When using the inside buoy markings do you believe your performance was better in lower (3/4 nm) or higher (1-1/2 nm) visibility? (Scenarios 4 versus 8)
- 2.8 Given one-side channel markings do you prefer the buoys to be on the inside or outside? (Scenarios 4 versus 5)

ADDITIONAL COMMENTS

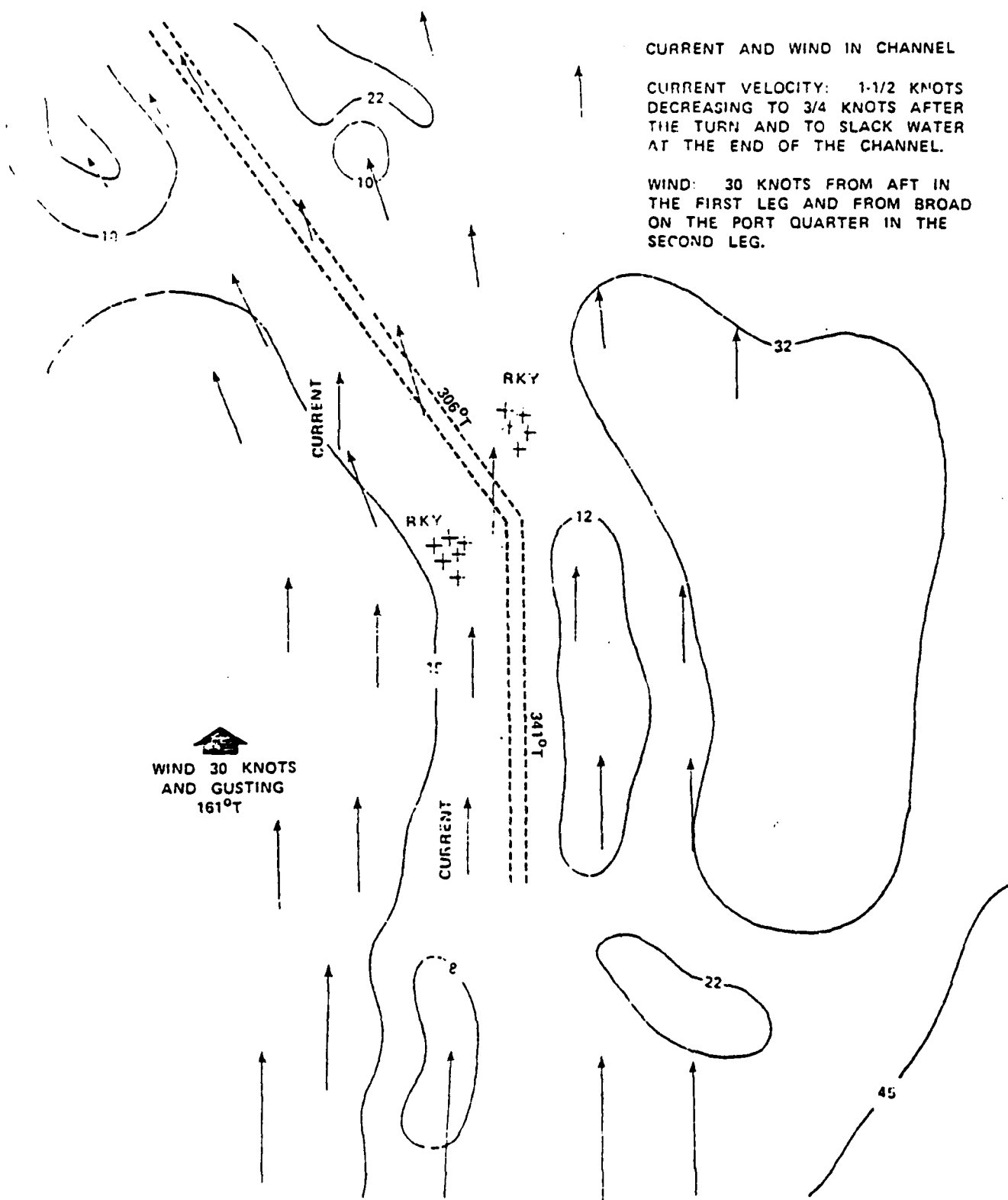


Figure B-1.

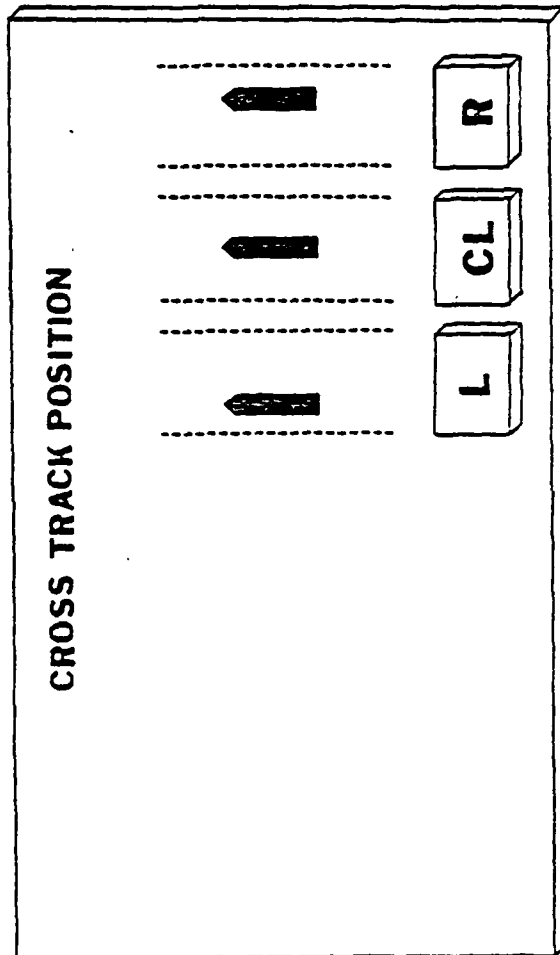


Figure B-2

## Appendix C

### WIND AND CURRENT VARIATIONS

#### C.1 INTRODUCTION

The wind and current variations are the same that were used in the Ship Variables experiment. (In the presimulation report for that experiment, they are compared to the effects in the Channel Width and CAORF experiments.) Both parameters are time varying functions which produce difficult (but realistic) piloting and steering tasks.

#### C.2 CURRENT

The current direction is constant throughout the one-side experiment. The magnitude of the current, however, decreases with elapsed simulation run time such that the current reaches 0 knots near the end of the scenario. The current direction and magnitude functions are listed below. A plot of current magnitude versus time is shown in Figure C-1.

##### Current Direction

$$TWC = 341 \text{ (degrees)}$$

Current flows towards this bearing.

##### Current Magnitude (calculated for four points (I) along the hull)

$$RVWC(I) = VWC(I) \cos \left[ (TMULT) (TMAIN + TADD) (\pi/180) \right]$$

where:

$$\begin{aligned} VWC(I) &= 2.5317 \text{ feet/second (1.5 knots)} \\ TMULT &= 2 \\ TMAIN &= \text{elapsed run time (minutes)} \\ TADD &= 18.0 \text{ (minutes) = initial offset time} \end{aligned}$$

#### C.3 WIND

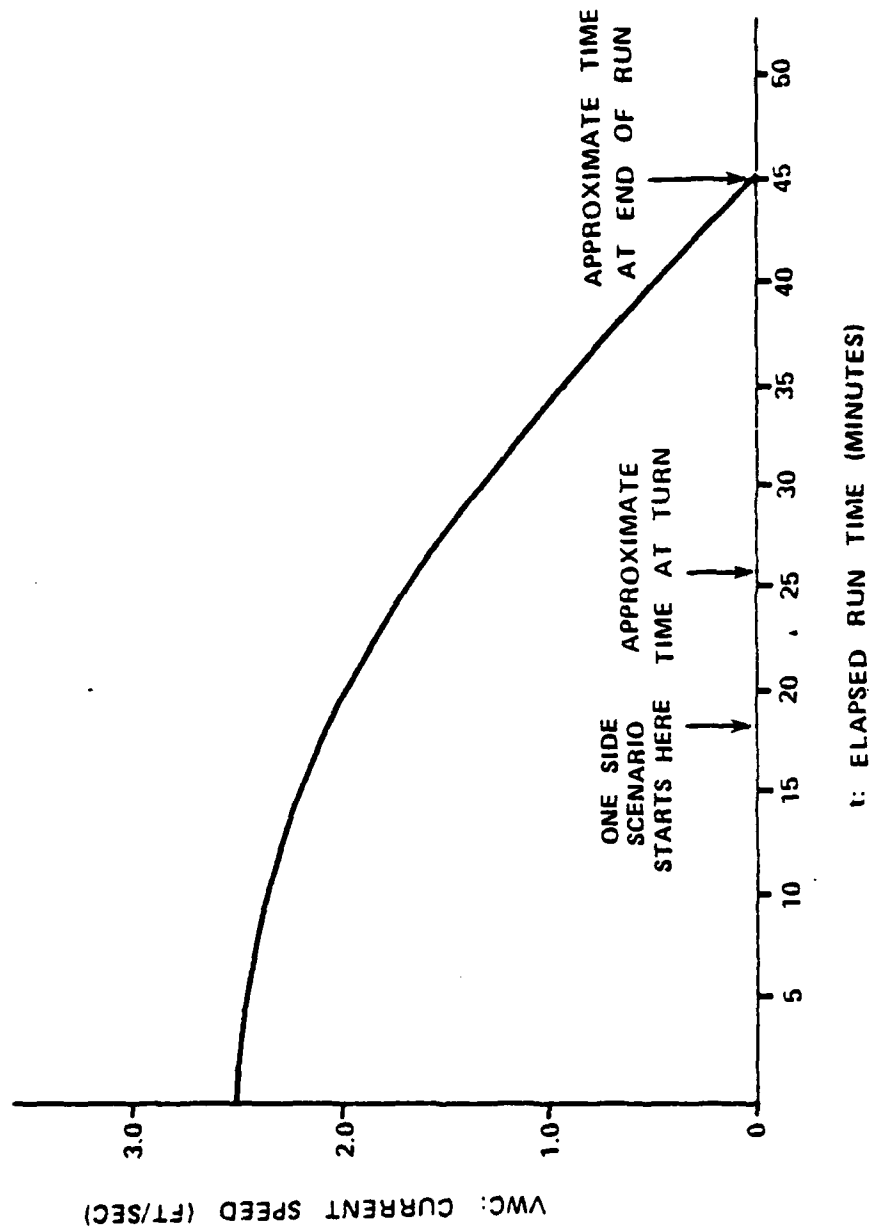
The wind direction and speed are both time varying. The wind functions for the one-side experiment are listed below. A plot of the magnitude function is shown in Figure C-2. A plot of the direction function is shown in Figure C-3.

##### Wind Speed

$$\begin{aligned} RWWS &= WWS + (0.0019) (TMAIN + TADD - 10.48) (WWS) \\ &+ (0.02) (WWS) \sin \left[ (TMAIN + TADD - 10.48) 2 \pi / 3 \right] \end{aligned}$$

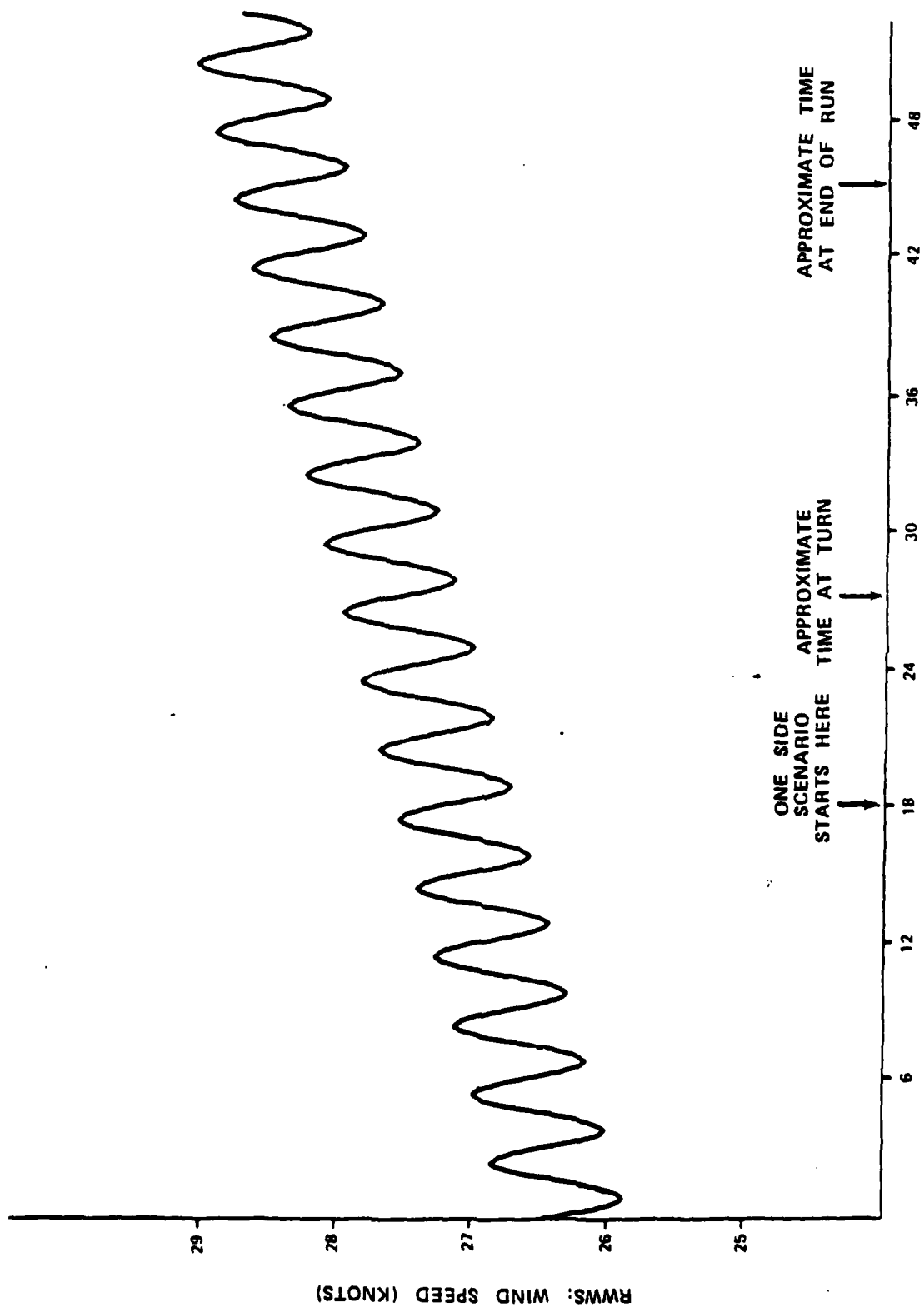
where:

$$WWS = 26.75 \text{ knots}$$



$$VWC = 2.53 \cos(t + t_0) \text{ ft/sec}$$

Figure C-1. Current Speed Function



ELAPSED RUN TIME (MINUTES)

Figure C-2. Wind Speed Function

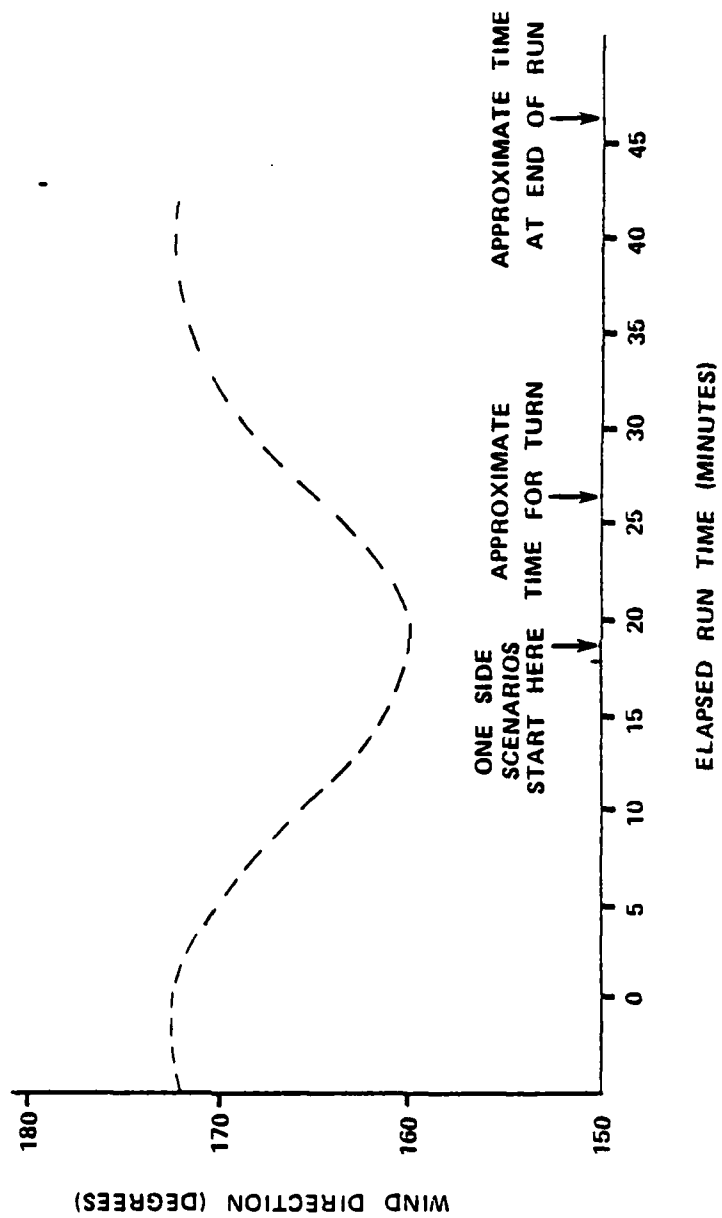


Figure C-3. Wind Direction Function

TADD = 18.0 (minutes)  
T1MAIN = elapsed run time (minutes)

Wind Direction

$$RWWD = WWD + (6) \cosine [(T1MAIN + TADD - 6)2 \pi / 36]$$

where:

WWD = 166 degrees (direction from which wind blows)  
T1MAIN = elapsed run time (minutes)  
TADD = 18.0 (minutes)

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